LAI Whitepaper Series
"Lean Product Development for Practitioners"

Program Management for Large Scale Engineering Programs

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1 About LAI

The Lean Advancement Initiative (LAI) at MIT, together with its Educational Network (EdNet), offers organizational members from industry, government, and academia the newest and best thinking, products, and tools related to lean enterprise architecting and transformation. LAI is a unique research consortium that provides a neutral forum for sharing research findings, lessons learned, and best practices.

LAI offers:

- unique opportunities to engage with customers, suppliers, and partners to solve problems and share organizational transformation experiences
- a portfolio of thought-provoking knowledge exchange events and meetings
- innovative enterprise transformation products, tools, and methodologies

LAI researches, develops, and promulgates practices, tools, and knowledge that enable and accelerate enterprise transformation. LAI accelerates lean deployment through identified best practices, shared communication, common goals, and strategic and implementation tools honed from collaborative experience. LAI also promotes cooperation at all levels and facets of an enterprise to eliminate traditional barriers to improving industry and government teamwork.

The greatest benefits of lean result when the operating, technical, business, and administrative units of an enterprise strive for enterprise-wide lean performance. LAI is completing its fifth Enterprise Value phase, during which LAI has engaged in transforming aerospace entities into total lean enterprises and delivered more value to all stakeholders than would have been possible through conventional approaches.

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2 About this Series

A vast amount of research has been conducted at MIT´s Lean Advancement Initiative (LAI) on Lean Product Development in the last 15 years. For the first time, this series of papers makes this research accessible to practitioners in a condensed form.

The aim is to provide an application-oriented, readable, concise and comprehensive overview of the main fields of Lean Product Development. The papers follow LAI´s understanding and philosophy regarding Lean Management concepts and especially their integration into large and complex Enterprise settings.

The papers draw mainly on the research done by LAI. Where necessary to ensure a comprehensive presentation of a topic, findings of other researchers and research groups from the field of Lean Product Development are integrated into the papers.

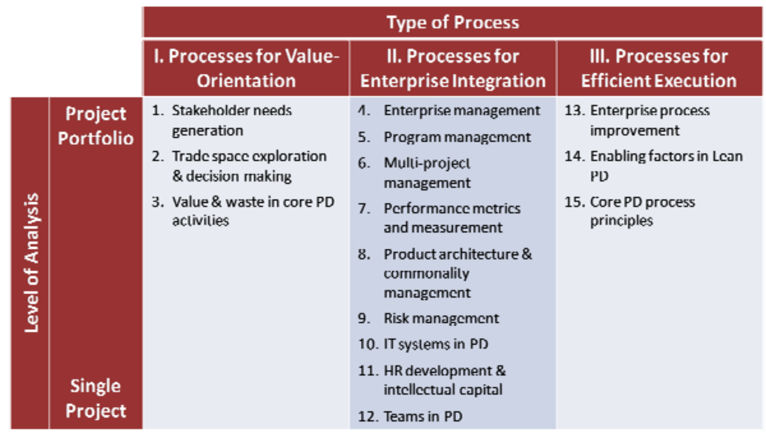

Figure 1: Topics of the Paper Series - LAI's Three Main Areas of Lean Product Development

The series focuses on 15 topics in three major areas of Lean Product Development that LAI identified (see Figure 1). The processes span the space from single project to project portfolio management. This paper addresses topics 4-6, summarizing them as Program and Multi-Project Management.

2.1 I: Processes for Value-orientation

The processes for value-orientation address those types of processes that ensure a focus on the creation of value and the elimination of waste in Lean Product Development. This covers the areas of stakeholder needs generation, trade space exploration and decision making, as well as the identification and handling of value and waste in the core PD processes.

2.2 II: Processes for Enterprise Integration

Enterprise Integration is one of the main challenges in developing a Lean Enterprise. Product Development plays a central role in this integration effort, as it interfaces with all main Enterprise processes. This therefore larger group consists of the processes of enterprise, program and multi-project management, performance metrics and measurement, product architecture and commonality management, risk management, IT systems, HR development and human capital, and teams in Product Development.

2.3 III: Processes for Efficient Execution

This group addresses the challenges surrounding the efficient execution of PD processes. It includes the relationship of PD to overall Enterprise process improvement initiatives, enabling organizational factors within Lean PD, as well as addressing alternative Lean PD core process principles.

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3 Summary and objective of this whitepaper

The goal of this whitepaper is to summarize the LAI research that applies to program management. The context of most of the research discussed in this whitepaper are large-scale engineering programs, particularly in the aerospace & defense sector.

The main objective is to make a large number of LAI publications – around 120 – accessible to industry practitioners by grouping them along major program management activities. Our goal is to provide starting points for program managers, program management staff and system engineers to explore the knowledge accumulated by LAI and discover new thoughts and practical guidance for their everyday challenges.

The whitepaper begins by introducing the challenges of programs in section 4, proceeds to define program management in section 5 and then gives an overview of existing program management frameworks in section 6. In section 7, we introduce a new program management framework that is tailored towards describing the early program management phases – up to the start of production. This framework is used in section 8 to summarize the relevant LAI research.

The authors wish to thank the LAI consortium members for their insightful comments and suggestions, most notably Tony Eastland, Don McAlister, Stuart Swalgen, Sean Dorey and Dustin Ziegler; the members of the Lean in Program Management Community of Practice, as well as our colleagues at MIT. The sole responsibility for any errors and inaccuracies remains with the authors. The views expressed in this document are those of the authors alone.

4 Introduction to Program and Multi-Project Management

This paper focuses on large-scale, engineering development projects. It draws mostly from insights in the aerospace and defense industry. These large-scale projects are referred to as ‘programs’. The generic term ‘project’ is used for smaller-scale efforts, e.g. the development of sub-systems within the program. These programs lead to the formation of ‘enterprises’. An enterprise is the interorganizational network that has the common purpose of the development and delivery of a system. An enterprise is comprised of both public organizations, such as the program office, as well as private organizations, such as the main contractor and its suppliers. As a result of the interorganizational nature of enterprises, they have distributed responsibility and leadership, and they have stakeholders with both common and diverse interests (Stanke, 2006).

Product development in these programs occurs through a complex network of human and physical resources, whose interactions utilize, transform and create knowledge that provides a new solution to a customer need. Large programs, with many stakeholders and relatively immature or unstable knowledge bases, produce risks. Some of these risks are mitigated or avoided, but others whether known or unexpected, are realized and turn into issues that impact cost and schedule. These issues result in significant cost and schedule overruns (see Figure 2): The F-35 Joint Strike Fighter is, for example, currently the most expensive program of all times, with a total cost overrun of 65% or $150 billion, and an increased price per plane of 81%, or $50 million. A program cost overrun of around 40% was the average in the last ten years for RDT&E costs (research, development, test & evaluation). As of 2009, the combined total cost overrun of major defense acquisition programs is estimated at $296 billion, with a 22 months average delay in delivery of the promised capability (GAO, 2010).

Breaking down the cost overrun into its main root causes is not easy, but three main areas emerge: Planning that was inaccurate or overly optimistic (e.g. regarding technology readiness or enterprise capabilities) leads to cost and schedule targets that cannot be achieved. This also includes understanding the stakeholder requirements, and the stability of these requirements. Changing stakeholder requirements can have a significant impact on cost overrun. Planning also involves the careful setup of contracts, so that risks and profits are fairly shared, as well as the incentives aligned properly. The second area is inefficient execution of the program. This includes sub-optimal organizational constructs, for example regarding the integration of program office, main contractor and suppliers. It also includes inefficient processes, consuming more resources or time than they could and should. The third factor is technological uncertainty that is added by immature technologies and not handled properly. All three areas are related to program management: Program management must ensure top-notch planning of complex engineering programs, the efficient execution of those programs in an admittedly complex enterprise organization, as well as balance and manage the need to include cutting-edge technology.

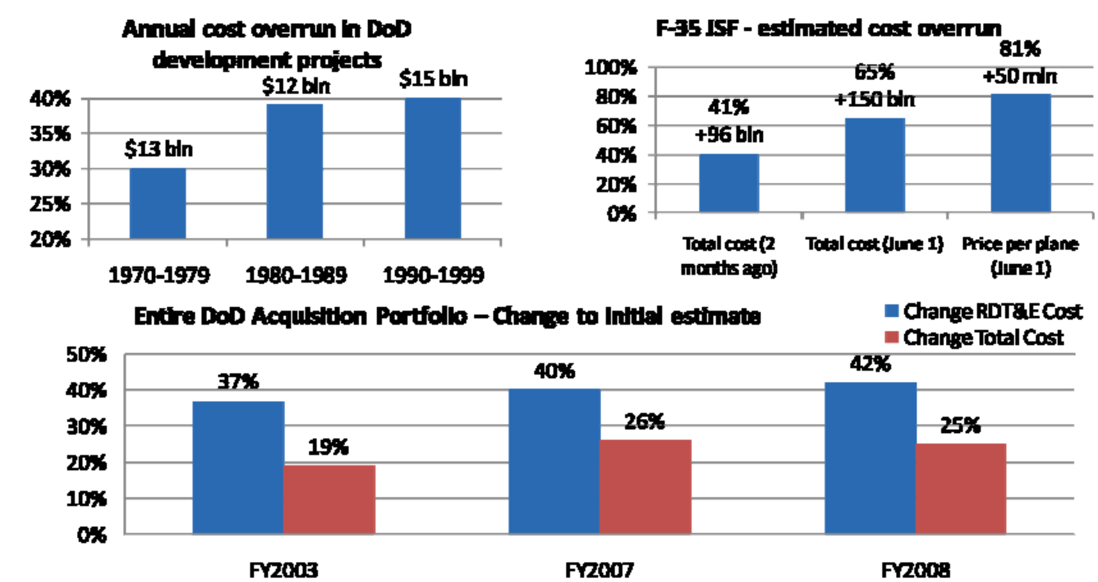

Figure 2: Examples of Cost and Schedule Overrun in DoD Programs (GAO, 2010, GAO, 2006, Capaccio, 2010)

Exactly quantifying the amount of cost overrun each factor contributes is difficult. Analyses of the relationship of technology maturity at program start to the final cost overrun of the project suggest that immature technology is responsible for about 30% of the total cost overrun. The remaining 70% are divided between the other two factors, insufficient planning and inefficient execution.

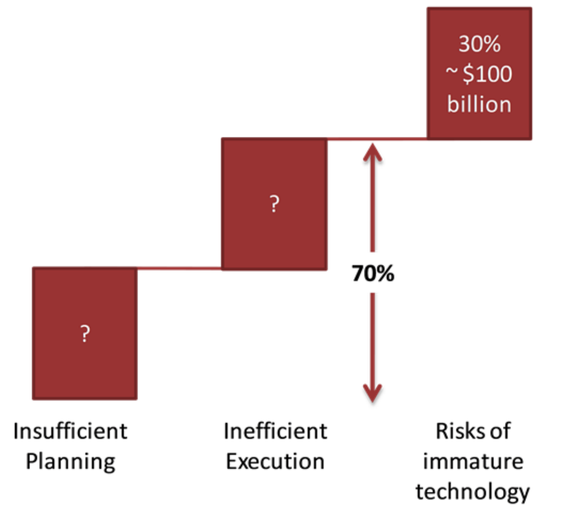

Figure 3: Estimation of Cost Overrun Contribution of Different Factors (adapted from GAO, 2010)

5 Defining Program Management

Program management is a diverse field, and a number of definitions for both "program" and "program management" exist. Table 1 gives an overview of possible definitions, in alphabetic order of author.

Table 1: Various definitions of program and program management (in alphabetic order of author)

Author	Definition of Program and / or Program Management
(Andersen and Jessen, 2003)	"A **program** could be a new product development, an organizational restructuring of the company or the implementation of an advanced software package in different departments of the company. **Program management** is the effective management of all the projects under the umbrella of the program."
(APM, 2006)	"**Program management** is the coordinated management of related projects, which may include related business-as-usual activities that together achieve a beneficial change of a strategic nature for an organization"
(Archibald, 2003)	"**Program**: A long-term undertaking that includes two or more projects that require close coordination."
(Brown, 2007)	"**Program Management** is management of a group of projects and/or operations to achieve business targets, goals, or strategies, and may or may not have a defined end point."
(DAU, 2010a)	"[**Program management** is] the process whereby a single leader exercises centralized authority and responsibility for planning, organizing, staffing, controlling, and leading the combined efforts of participating/ assigned civilian and military personnel and organizations, for the management of a specific defense acquisition program or programs, through development, production, deployment, operations, support, and disposal."

Author	Definition of Program and / or Program Management
(Ferns, 1991)	"A **program** is a group of projects that are managed in a coordinated way to gain benefits that would not be possible were the projects to be managed independently. […] **Program management** is the coordinated support, planning, prioritization and monitoring of projects to meet changing business needs."
(Haughey, 2001)	"**Program management** is a technique that allows organizations to run multiple related projects concurrently and obtain significant benefits from them as a collection. Program management is a way to control project management, which traditionally has focused on technical delivery. A group of related projects not managed as a program are likely to run off course and fail to achieve the desire outcome."
(Hut, 2008)	"[…] **program management** is the definition and integration of a number of projects to cause a broader, strategic business outcome to be achieved. Program management is not just the sum of all project management activities but also includes management of the risks, opportunities and activities that occur 'in the white space' between projects."
(Lycett et al., 2004)	"**Program Management** – defined as the integration and management of a group of related projects with the intent of achieving benefits that would not be realized if they were managed independently. Whilst connected, this is distinct from portfolio management."
(Mao et al., 2008)	"[…] a **Program** consists of a series of interrelated projects while **Program Management** is to manage all interrelated projects as a whole in a harmonic manner which is beneficial to successfully fulfill each single project and the entire program."
(OGC, 2007)	"A **program** is defined as a temporary, flexible organization created to coordinate, direct and oversee the implementation of a set of related projects and activities in order to deliver outcomes and benefits related to the organization's strategic objectives. A program is likely to have a life that spans several years. […] **Program management** is the coordinated organization, direction and implementation of a dossier of projects and transformation activities (i.e. the program) to achieve outcomes and realize benefits of strategic importance."
(Patanakul and Milosevic, 2008)	"[…] a **program**, led by a program manager, is a family of projects that are strongly dependent, share common goals, and lead to a single deliverable product or service."
(Patanakul and Milosevic, 2009)	"Another case of MPM [multi-project management] is **program management**, where the projects in the group are mutually dependent, share a common goal, and lead to a single deliverable product or service. In contrast with MGMP [management of a group of multiple projects], program management is the centralized coordinated management of a group of goal-related projects to achieve the program's strategic objectives and benefits."
(PMI, 2008b)	"**Program Management** is the centralized coordinated management of a program to achieve the program's strategic objectives and benefits. It involves aligning multiple projects to achieve the program goals and allows for optimized or integrated cost, schedule, and effort."

By comparing these definitions, five key aspects of programs and program management emerge:

1. **A program consists of multiple, related projects.** The first aspect in which all definitions for program management found in current literature agree (except for one) is that a program consists of multiple projects. Programs may also evolve from single projects as they become more complex. The organization of the projects within a program can vary depending on the purpose of the program. Projects can be organized sequentially, run in parallel as hybrid sequential-parallel models, or be organized as a network of interlinked projects. However, the most common concept of the organization of projects within a program is an environment of interlinked projects.
2. **Long program duration.** The second aspect focuses on the duration of a project or program. Whereas projects are time constrained, programs in general do not need to have a fixed end date. A program can only come to an end when the deliverable (e.g., a product or service) is fully developed and handed over to the user/customer. In addition, some authors state that a program is also responsible for the time after handing over the product or service to the user. This may include, for example, deployment, operations, support, and disposal.
3. **Management economy of scale.** There are many tasks and objectives in the projects within a program that are similar. By identifying best practices among different projects and introducing organization-wide learning, huge benefits can be gained when projects are managed in a program instead of being managed in isolation in a project management context.
4. **Complex value proposition.** A program focuses on multiple stakeholders and has to satisfy a complex value proposition. While a single project may only deliver an output such as a product, a program has to satisfy the multifaceted needs of several stakeholders. A program could, for example, provide a transportation solution for urban environments, while the project would deliver a train or bus for this purpose.
5. **Programs define their own enterprise.** Based on the research undertaken by the LAI, the formation of a program enterprise is included in the definition of program management used in this thesis. The organization of each program is unique and established to satisfy the needs of all stakeholders in the best way. Since a program has its own program office and has to defend decisions against undue influence from single stakeholders, a program has a certain degree of autonomy.

Therefore, we define program management in the context of this whitepaper as follows:

“Program management is defined as the management of multiple related projects and the resulting enterprise over an extended period of time to deliver a complex value proposition and utilize efficiency and effectiveness gains.”

6 Overview of Existing Program Management Guidelines

A number of industry and government organizations provide guidelines for program management. While we cannot present all relevant standards, this section will introduce relevant documents from the US Department of Defense, the Project Management Institute, and the UK Office for Government Commerce (OGC).

DoD Decision Support System
- Strategic planning and resource allocation
- Determination of capability needs
- Acquisition of systems

Defense Acquisition Program Goals and Strategy
- Acquisition Program Baseline
- Technology Development Strategy
- Program Acquisition Strategy

Affordability and Life Cycle Resource Estimates
- Affordability of progams
- Resource estimation

Systems Engineering
- System design
- SE process

Life Cycle Logistics
- Logistics from concept phase to disposal

Human Systems Integration
- Integration of human capabilities in the SE process

Acquiring Information Technology
- IT system design
- Net-centric system design

Intelligence, Counterintelligence and Security Support
- Protecting research and technology knowledge

Integrated Test & Evaluation
- Develop robust and integrated T&E strategy

Decisions, Assessments and Periodic Reporting
- Preparation for milestone reviews and decisions

Remaining Program Management Activities:
- Integrated Program Management
- Risk Management
- Integrated Product and Process Development,
- Earned Value Management and others

Figure 4: Program Management Elements according to Defense Acquisition Guidebook (DAU, 2010a)

The work on program management carried out at LAI stands in the context of a number of different bodies of knowledge. First and foremost, the Department of Defense Instruction

5000.02 describing the operation of the acquisition system (DoD, 2008). The content of the DoDI 5000.02 is supported by additional detail and best practices outlined in the Defense Acquisition Guidebook (DAU, 2010a), summarized in Figure 4.

In addition to the Guidebook, the Defense Acquisition University also offers a number of courses that are relevant to program management. Among others, these include ACQ-101: Fundamentals of Systems Acquisition Management, ACQ-201: Intermediate Systems Acquisition Course, PMT-251: Program Management Tools, and PMT-352: Program Management Office Course (DAU, 2010b). The course content is summarized in Figure 5.

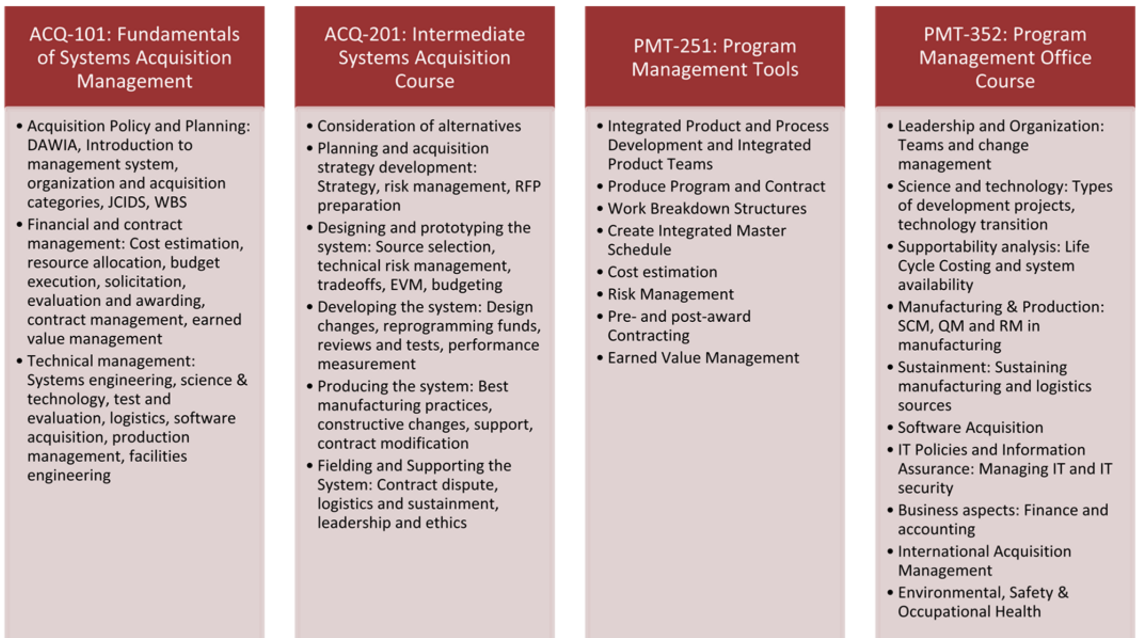

Figure 5: Selection of DAU courses and content on Program Management (DAU, 2010b)

Two major, generic standards for program management exist: The PMI Program Management Standard, currently in its 2nd edition (PMI, 2008b), and the OGC standard Managing Successful Programmes, MSP (OGC, 2007).

PMI groups program management activities into 5 program management process groups and 12 knowledge areas (PMI, 2008b). The activities in each knowledge area are structured along the process groups:

- **Program management process groups:** Initiating process, planning process, execution process, monitoring and control process and closing process
- **Knowledge areas:** Integration management, scope management, time management, cost management, quality management, human resource management, communication management, risk management, procurement management, financial management, stakeholder management and program governance.

The OGC standard consists of three major elements (see Figure 8):

1. **Transformational Flow:** Identifying a program, defining a program, managing the program tranches, delivering the capability, realizing the program benefits and closing a program
2. **Governance Themes:** Organization, Vision, Leadership and stakeholder engagement, benefits realization management, blueprint design and delivery, planning and control, business case, risk management and issue resolution, and quality management.

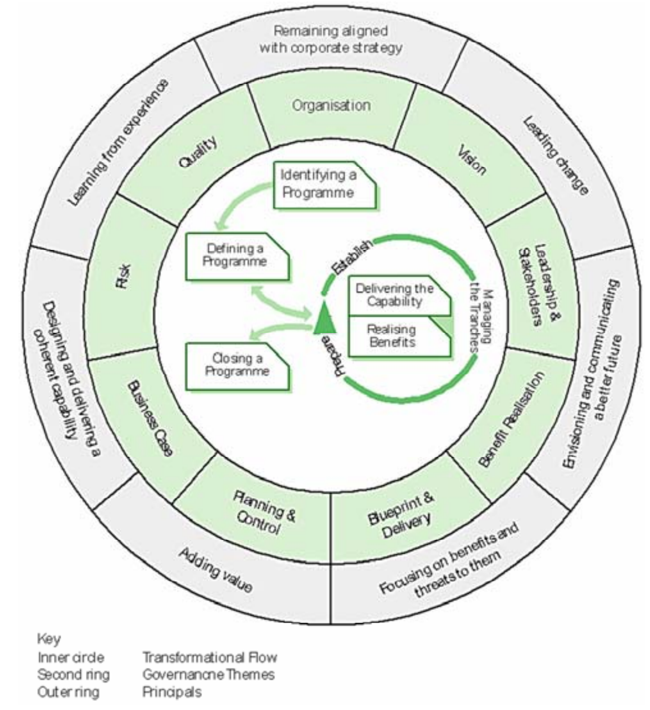

Figure 6: Structure of the OGC 'Managing Successful Programmes' standard (from OGC, 2007)

3. **Program management principles:** Remaining aligned with corporate strategy, leading change, envisioning and communicating a better future, focusing on the benefits and threats to them, adding value, designing and delivering a coherent capability, and learning from experience.

Based on the recent PMI Role Delineation Study (PMI, 2011), a new framework emerged to structure program management activities: The 5 program management performance domains (see Figure 7). The program management performance domains are:

- **Program strategy alignment:** Identifying opportunities and benefits that achieve the organization's strategic objectives through program implementation

Figure 7: 5 Program Management Performance Domains (Norman, 2011)

- **Program benefits management:** Defining, creating, maximizing, and sustaining the benefits provided by programs.
- **Program stakeholder engagement:** Capturing stakeholder needs and expectations, gaining and maintaining stakeholder support, and mitigating / channeling opposition
- **Program governance:** Establishing processes and procedures for maintaining pro-active program management oversight and decision-making support for applicable policies and practices throughout the entire program life cycle.
- **Program lifecycle management:** Managing all the program activities related to program definition, program benefits delivery and program closure

Another relevant resource for Program Management is the project management literature, as programs often contain a large number of projects that must be guided and coordinated thorough program management. Two major overlapping frameworks exist: the Project Management Institute with the Project Management Body of Knowledge (PMI, 2008a), and the PRINCE2 framework developed in the UK by the Office of Government Commerce (OGC, 2009). Fundamentally, both provide scalable and detailed project management guidelines. Whereas the PMI approach places more emphasize on the different knowledge areas and application processes of project management (such as scope and time management), the PRINCE2 approach focuses more on managing project stages and their transitions. The content of the guidelines is summarized in Table 2.

The following sections will discuss the contributions that LAI research has made to the management of large-scale engineering programs. The structure of the LAI contributions do not follow any particular program management standard, but will be mapped to the program management standards and models discussed before for reference.

Table 2: Comparison of Project Management Standards

Content of PMI Project Management Body of Knowledge (PMI, 2008a)	Content of OGC PRINCE2 Standard (OGC, 2009)
• **Project Life Cycle and Organization:** Project phases, stakeholders, organizational integration • **Project Management Processes:** Project initiating, planning, executing, monitoring and closing • **Project Integration Management**: Project charter, management plan, coordination of processes • **Project Scope Management:** Requirements, scope, WBS, verify and control scope • **Project Time Management:** Define and sequence activities, estimate resources and duration, develop and control schedule • **Project Cost Management:** Estimate costs, determine and control budget • **Project Quality Management:** Plan quality, quality assurance and control • **Project HR Management:** HR plan, acquire, develop and manage project team • **Project Communication Management:** Stakeholders, communication plan, information distribution and reporting, stakeholder expectations • **Project Risk Management:** Plan, identify, analyze, mitigate, monitor and control risks • **Project Procurement Management:** Plan, conduct, administrate and close procurement	• **Project Management Principles:** Continued business justification, learning from experience, defined roles and responsibilities, manage by stage, manage by exceptions, focus on product, tailor process • **Project Management Themes:** Business case, organization, quality, plans, risk, change, progress • **Starting up a project:** Project manager and team appointment, project description, project approach • **Initiating a project:** Project planning, business case and risk analysis, project controls, project initiation document • **Directing a project:** Authorizing initiation, project and stages, giving ad-hoc directions, confirming project closure • **Controlling a stage:** Work packages, progress assessment, project issues, reviewing status, reporting, correct or escalate issues, receive completed work package • **Managing stage boundaries:** Planning stages, updating project plan and business case, updating risk log, report stage end • **Managing product delivery:** Linking project and team leaders by accepting, executing and delivering work packages • **Closing a project:** decommissioning project, identify follow-on actions, project review

7 Program Management within the Scope of LAI's Research

7.1 Structure of LAI Program Management Framework

The research summarizes in this paper focusses on the early phases of program management, up to the start of production. Significant part of programs may lie in those life cycle phases not addressed by this document. However, the overall program organization and enterprise management aspects are still relevant for these phases.

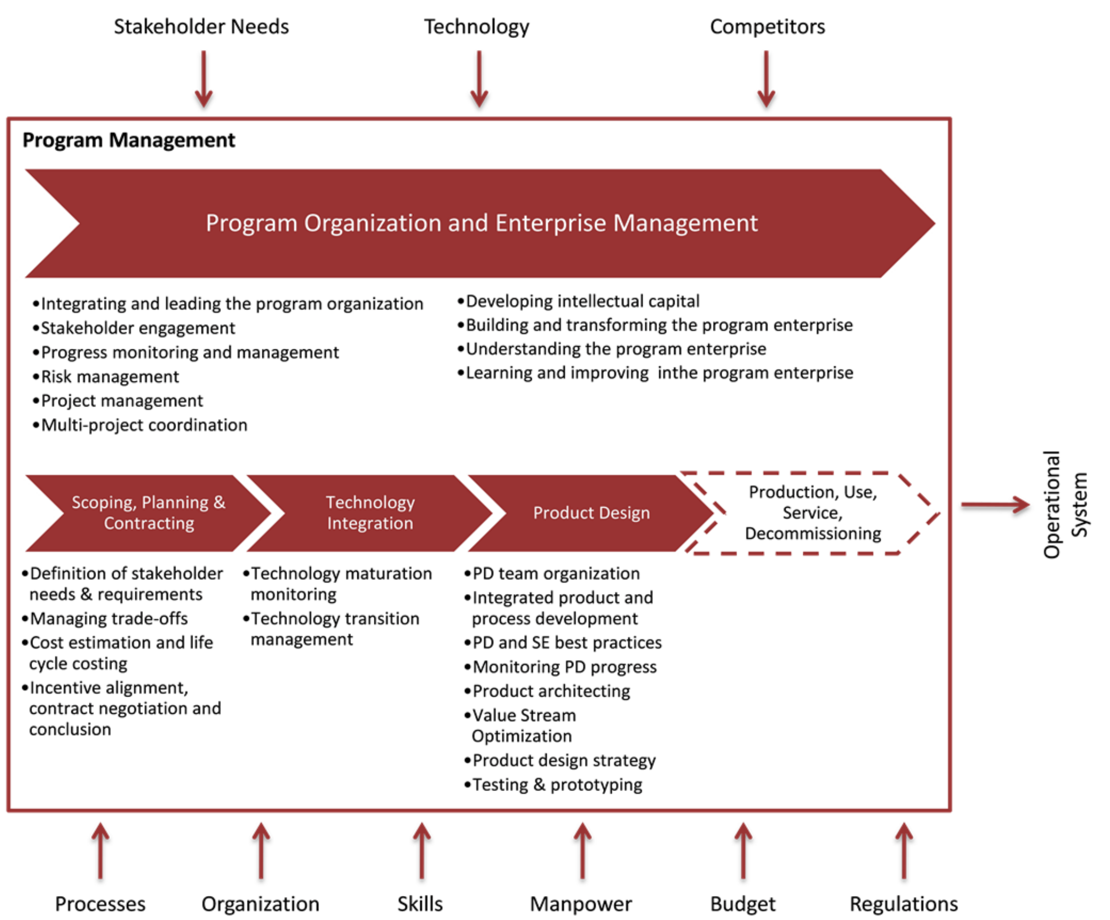

Figure 8: Aggregated Structural View of Program Management

Figure 8 structures Program Management along four main activities that will be used to summarize the related LAI research: Program Organization and Enterprise Management; Scoping, Planning & Contracting; Technology Integration; Product Design; and Production, Use, Service and Decommissioning. As this document focuses on the design- and development-related phases of Program Management, the Production phase and following life cycle phases are not within its scope. While the model provides a logical structure for important processes, it does not represent a strict 'timeline' for the execution. While for example cost estimation is important when evaluating different proposals during contracting, it is also important to update program plans during technology development and product design. Programs can be expected to go through several spirals of planning, technology integration and design. Each of the four main activities contains a number of core competencies that are discussed in the following subsection. The LAI research contributions are mapped onto these core competencies in section 7.

The framework consists of four main elements: Program organization and enterprise management; Scoping, planning and contracting; Technology development; and Product design. This framework covers a program from the decision for material development to the start of production. The framework focuses on the processes and organizational practices that are important for the successful program execution from both a government Program Office perspective, as well as program management from the contactors perspective (see Figure 9). Whereas some practices in the model explicitly focus on the interaction between and within the government and the main contractor, many recommendations are also valid for the extended program enterprise. That is, the recommendations are also valid within and for interactions between the main contractor and the system suppliers, the system suppliers and their suppliers and so forth.

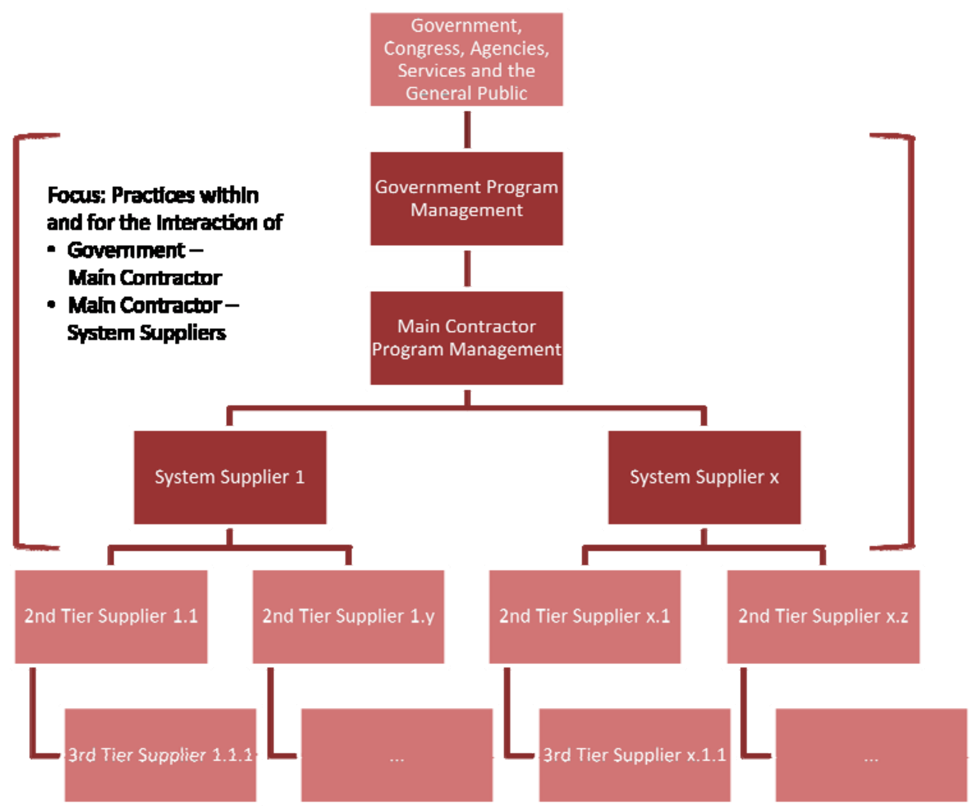

Figure 9: Simplified Representation of Program Enterprise Stakeholders

The LAI research does not follow any particular program management standard, but can be mapped onto the existing standards (see Table 3).

Table 3: Mapping of LAI Program Management Elements to Existing Standards

	Program Organization and Enterprise management	Scoping, Planning & Contracting	Technology Integration	Product Design
Managing Successful Programmes (OGC, 2007)				
Transformational Flow	X			
Governance	X			
Program Management Principles	X			
PMI Program Management Standard, 2nd edition (PMI, 2008b)				
Program management process groups	X			
Program management knowledge areas	X			
PMI Program Management Performance Domains (Norman, 2011)				
Program strategy alignment	X			
Program benefits management	X	X		
Program stakeholder engagement	X	X		
Program governance	X			
Program lifecycle management		X	X	X

7.2 Overview of Program Management Core Competencies

In general, the Program Management function coordinates the transformation of various input factors, such as stakeholder needs, technology, competitive actions, process definitions, organization, skills, manpower, allocated budget, regulations etc., into the final product, an operational system. There are many ways to structure the program "black box". The representation in Figure 8 is clustered around the core competencies of a program enterprise to successfully deliver the operational system, given a certain set of input factors, or resources. These consist of the four main areas of Program organization and enterprise management; Scoping, planning & contracting; Technology development; and Product design. As the LAI research focuses on the early phases of a system's life cycle, the phases of production, use, service, refurbishment and decommissioning are not covered in this model.

Program Organization and Enterprise Management consists of two main parts: **Program organization (8.1)** focuses on the practices to efficiently execute a program between the government program office, the main contractor and the system suppliers. **Program Enterprise Management (8.2)** addresses more generally those aspects that are important in creating, understanding and improving large and complex enterprises. Program organization encompasses activities such as

- **Integrating and leading the program organization** (8.1.1): This section addresses how the main organizations of the program enterprise, i.e. program office, main contractor and system suppliers, interact most effectively, and how this complex organization can be managed.
- **Stakeholder engagement** (8.1.2): Programs are always dynamic, as even the shortest programs usually cover several years. Stakeholder needs and the program environment continually change, and stakeholder engagement is key to integrate changing stakeholder needs in the program, as well as allow the stakeholders to make informed decisions on the program (e.g. cost/benefit tradeoffs for changing requirements, renewal or extension of budgets etc.).
- **Progress monitoring and management** (8.1.3): It addresses the need to understand, track and manage the progress of the program and informs the corrective actions when necessary. Earned Value Management (EVM) is one example of such a tool.
- **Risk management** (8.1.4): This is an activity that makes the key program risks transparent, ensures that the understanding of risks is closely linked to the decision making process, strives to reduce uncertainty as much as possible, and account for residual uncertainty and risk with robust processes and systems.
- **Project management** (8.1.5): The activities include managing the execution of and transition between the different phases of the program, as well as the management of scope, time, budget and quality of the program (see Table 2 for a detailed summary).
- **Multi-project coordination** (8.1.6): In addition to the challenges of managing a single project, program offices execute several projects in parallel, as well as contractors and suppliers on the different levels also usually have more than one project that they work on in parallel. This generates specific challenges, such as the allocation of resources, especially the staffing of the different projects in parallel along their specific life cycles.

The category of **Program Enterprise Management (8.2)** contains the following core competencies:

- **Developing intellectual capital** (8.2.1): Companies and government organizations must provide incentives to their employees to develop deep technical knowledge and expertise in relevant areas. This includes encouraging and rewarding life-time careers as technical experts, for example through technology-oriented career towards senior engineers.
- **Building and transforming the program enterprise** (0): Architecting the enterprise of both public (government) and private (companies) organizations that are involved in executing the program and creating stakeholder value. Transforming existing

enterprises along an enterprise transformation roadmap to re-align them with stakeholder needs and optimize the value flow throughout the enterprise.
- **Understanding the program enterprise** (8.2.3): Assessing existing program enterprises to benchmark them against best practices and/or other program enterprises, as well as to uncover areas for improvement.
- **Learning and improving in the program enterprise** (**Error! Reference source not found.**): Successfully managing continuous improvement and organizational change in complex enterprises.

During **Scoping, Planning & Contracting (8.3)**, the user needs are translated into a legal contract between the program office and the main contractor. As part of this, the life cycle strategy for the entire program is planned and codified, spanning system development, technology transition, operational use and sustainment, as well as future technology refresh and ultimate system disposal. This step includes the following activities:

- **Stakeholder needs & requirements definition** (8.3.1): The stakeholders in large programs are numerous and varied, and so are the resulting needs. Stakeholders from different areas – government, congress, users, general public, contractors etc. – and different levels of the hierarchy – top management to shop floor – have to be taken into account. This requires a sophisticated process for eliciting and aligning these diverse needs.
- **Managing trade-offs** (8.3.2): During the specification of the final requirements, conflicting requirements have to be traded against each other. This includes for example trade-offs regarding cost, schedule, performance and risk requirements. The management of trade-offs must also include re-visiting and re-negotiating requirements where necessary, in order to assure that the baseline requirements are realistic.
- **Cost estimation & life cycle costing** (8.3.3): Before a budget is allocated, the resource requirements in term of cost, schedule, manpower, facilities and other resources has to be forecasted. This involves a probability-based assessment of these resources so an informed decision can be made in the following step regarding the type and content of the contract.
- **Incentive alignment, contract negotiation & conclusion** (0): Contracting under large program risks is a very challenging task. Based on the cost (and other resources) probability distributions, an adequate way of sharing risk (cost overrun relative to baseline) and profit (cost savings relative to baseline) has to be developed. This should allocate the responsibility for carrying risk consequences according the responsibility for the risk sources, or create incentives to accept external risks. An important part of this process is understanding and aligning incentives between the program office and the contractors, as well as between contractor and its suppliers. Incentives must include guidelines on how to share benefits from local and

enterprise-level improvements, improvements strategies, as well as guidelines for recovering stressed relationships.

During **Technology Integration (8.4)**, technologies for the design phase are selected and integrated into the program. The readiness of low-maturity technologies may be increased in parallel technology development tracks to a level that is suitable for their introduction into the design process. It includes the following activities:

- **Technology maturation monitoring** (8.4.1): The main objective is to develop technologies to a level where the main risks regarding their cost and performance have been eliminated and they are fit to be integrated into an overall system. However, assessing the maturity level of a technology is not a trivial task, as certainty regarding its development status may be difficult to establish.
- **Technology transition management** (8.4.2): This process addresses the integration of technologies that just reached sufficient maturity levels at R&D facilities into existing design and production processes at the main contractor and its suppliers.

In **Product Design (8.5)**, the system integration and its components are specified to a level that makes it fit for production. It consists of the following activities:

- **Product Design team organization** (**Error! Reference source not found.**): Product Design is a complex task that relies heavily on the integration of deep domain knowledge from various areas. This places high requirements not only on the leadership of PD teams, but also on the team members and the organization that provides them. In addition, integrated product teams for example bridge the gap between different organizations.
- **Integrated product and process development** (8.5.2): As requirements and systems vary, the PD process has to be adapted accordingly. This is closely linked to the optimization of the value stream, for example with value stream mapping and the elimination of waste, as well as the selection of an appropriate development strategy, such as a waterfall model or set-based design.
- **Product Design and System Engineering best practices** (**Error! Reference source not found.**): Some organizational concepts as well as processes have been identified as especially important for success. These are summarized in best practices that can be used for an internal benchmarking and to identify opportunities for improvement.
- **Monitoring Product Design progress** (8.5.4): Monitoring progress during PD can be particularly challenging, as many iterations and re-work of “finished” components may occur. Therefore, to allow for a better management of the process, the use of appropriate KPIs and leading indicators is very important.
- **Product architecting** (0): The architecture of a product has important implications on the fulfillment of customer requirements (e.g. modularity to allow for partial and continuous upgrades during the life cycle, decoupling of technology development

cycles etc.). It also has a significant influence on how the PD process can be organized most effectively.

- **Value Stream Optimization** (0): The creation of stakeholder value is the ultimate goal in product design. Several tools from Lean Product Development are available to model and improve the flow of value while eliminating waste. The challenge lies in the identification of value and discerning wasteful activities from necessary, but non-value creating activities.
- **Product Design strategy** (8.5.7): A number of strategies or process families can be chosen for a design that have strong implications for all other program processes and the way that users and customers are integrated. These include evolutionary acquisition, waterfall model and set-based design.
- **Testing and prototyping** (8.5.8): This activity is relevant both to technology development as well as product design. In technology development, the testing and prototyping would focus on single components or technologies, whereas in product design, the entire system (or major components) would be tested. This is the main activity to verify that a certain performance level has been reached, and component and system requirements are met. Developing testing and prototyping protocols that assure a necessary level of certainty while minimizing cost is a very challenging task.

8 LAI's Insights on Program Management

8.1 LAI's Insights: Program Organization

In the following, the LAI insights regarding the different areas of program organization and enterprise management are briefly summarized.

8.1.1 Integrating and leading the program organization

This section addresses how the main organizations of the program enterprise, i.e. program office, main contractor and system suppliers, interact most effectively, and how this complex organization can be managed.

Publication Title & Synopsis	Citation & Download Link
Stanke, A. K. (2006) Creating High Performance Enterprises, PhD Thesis, LAI and Massachusetts Institute of Technology.	(Stanke, 2006) Download Link
There are a small number of exceptional programs that have managed to meet all of their commitments in terms of cost, schedule, and technical performance simultaneously. This work explores these programs on a case-by-case basis. Best practices from these programs are organized into a framework of factors that differentiate these high performing programs from the majority of others that struggle in the same environment. These factors are: 1. Distributed Leadership Action: 1.1 Boundary spanning activity across organizations in the enterprise; 1.2Developing and utilizing a social network; 1.3 Developing and sustaining extensive customer interactions; 1.4 Fostering and maintaining personal accountability of plans and outcomes; 2. Informal Structures: 2.1 Boundary spanning activity with the enterprise environment; 2.2 Encouragement for open information sharing; 2.3 Veteran core group to institutionalize behavior; 3. Formal Structures: 3.1 Balanced risk through work share and teaming arrangements; 3.2 Common contract structure; 3.3 Standardized program management practices (metrics and reporting system)	
Wirthlin, J. R. (2009) Identifying Enterprise Leverage Points in Defense Acquisition Program Performance, PhD Thesis, LAI and Massachusetts Institute of Technology.	(Wirthlin, 2009) Download Link
The program management office on the government side has a decisive influence on the performance of a program. This work explores program office management practices. Based on interviews with senior program managers and decision makers at the Air Force, key decisions and principles of running a program office were collected. A simulation model was set up to explore the impact that these decisions and principles had on the duration of a program to start of production, regarding both the average duration as well as the variation in duration. Of the 20 possible actions, combined actions showed the biggest impact. The top five single actions to reduce overall program duration were 1. Ability to kill programs at milestones; 2. Guaranteed funding stability; 3. Reduction of technical uncertainty; 4. Improve success at Critical Design Reviews and 5: Eliminate wait time for Acquisition Panel activities.	
Morgan, S. (1999) The Cost and Cycle Time Implications of Selected Contractor and Air Force System Program Office Management Policies during the Development Phase of Major Aircraft Acquisition Programs, Master Thesis, LAI and Massachusetts Institute of Technology.	(Morgan, 1999) Download Link
This work develops a different simulation model that analyzed government program office management policies and especially workforce development and staffing policies The focus was again the analysis on the impact on program schedule. The main	

findings were: 1. There is a strong dependence between government program office performance and contractor performance; 2. Project compression, i.e. schedule reduction, is difficult to achieve by increasing the workforce beyond a certain limit; 3. High workforce turnover is detrimental to program success; 4. Low military tenure is detrimental to program success; and 5. Government program office workforce size is critical for success.	
McNutt, R. T. (1998) Reducing DoD Product Development Time: The Role of the Schedule Development Process, PhD Thesis, LAI and Massachusetts Institute of Technology.	(McNutt, 1998) Download Link
The issue of schedule overruns in programs is further explored in this work, based on detailed interviews with key stakeholders from the Pentagon, program offices and industry contractors. The aim was to identify the key reasons for schedule overruns and develop recommendations for improvements. The main issues leading to long program schedules are 1. Lack of leadership on cycle time; 2. Lack of schedule-related information and tools; 3. Lack of schedule-based incentives; and 4. Overriding influence of funding-related constraints. The derived recommendations are 1. Provide clear leadership on cycle time reduction; 2. Develop and use schedule-based information; 3. Provide incentives for cycle time reduction; and 4. Mitigate funding-based constraints on development projects	

8.1.2 Stakeholder engagement

Programs are always dynamic, as even the shortest programs usually cover several years. Stakeholder needs and the program environment continually change, and stakeholder engagement is key to integrate changing stakeholder needs in the program, as well as allow the stakeholders to make informed decisions on the program (e.g. cost/benefit tradeoffs for changing requirements, renewal or extension of budgets etc.).

Publication Title & Synopsis	Citation & Download Link
McKenna, N. (2006) The Micro-foundations of Alignment among Sponsors and Contractors on Large Engineering Projects, Cambridge, MA, Master's thesis, MIT and LAI.	(McKenna, 2006) Download Link
A contributing factor to the cost, schedule and performance challenge of large projects is that the project enterprise is created by separate firms being brought together by the project sponsor. Success requires multiple firms working together to efficiently create complex product systems. In an attempt to improve project outcomes, sponsors often endeavor to create "alignment" between themselves and their key contractors. In practice, alignment has proved difficult to create and to sustain. This research explores the policies and actions taken by firms that give rise to alignment. The large engineering projects studied for this research were offshore oil and gas field developments. The research revealed that alignment is founded on the collective understanding of the project, incorporating the firm's separate interests, and inter-firm trust. Furthermore the two antecedents of alignment act together to form a self-enforcing alignment mechanism. Six factors (system architecture, organizational design, contract design, risk, metrics and incentives) were identified that establish the inter-firm interactions through which collective understanding and inter-firm trust are created. These findings are organized into a framework that guides policy selection with a view to enabling the generation, and sustainment, of alignment.	
McVey, M. E. (2002) Valuation Techniques for Complex Space Systems: An Analysis of a Potential Satellite Servicing Market Cambridge, MA, Master's thesis, LAI and MIT.	(McVey, 2002) Download Link
Current financial valuation techniques fail to capture several important aspects of	

technical projects, including flexibility and the interface between economics and technology. Additionally, valuations rarely aid in the process of determining which service or product provides value to both the client and the provider. This thesis presents a new valuation framework that accounts for these downfalls by breaking the valuation analysis into two distinct parts: the client's value and the provider's value. The client value analysis is a necessary step in determining the provider's value, as it provides the basis for the revenue the provider will generate as well as an idea of which type of service or product provides the most value to the client. As a viable market does not exist without both a client and a provider, it is necessary to look at a project from both perspectives. The valuation framework is used to analyze the commercial geosynchronous satellite servicing market.

8.1.3 Progress monitoring and management

This area addresses the need to understand, track and manage the progress of the program and informs the corrective actions when necessary. Earned Value Management (EVM) is one example of such a tool.

Publication Title & Synopsis	Citation & Download Link
Blackburn, C. D. (2009) Metrics for Enterprise Transformation, Cambridge, MA, Master's thesis, MIT and LAI.	(Blackburn, 2009) Download Link
The objective of this thesis is to depict the role of metrics in the evolving journey of enterprise transformation. Two case studies were performed, considering: 1. The implementation of a bottom-up measurement system to drive transformation and 2. The effect of a top-down corporate measurement system on the enterprise. The Lean Advancement Initiative's Enterprise Transformation Roadmap was used as a method for depicting how performance measurement can help enable enterprise transformation. The implications of research in metrics for enterprise transformation span across three areas: 1. The extensive literature reviews provide an academic contribution for performing enterprise and measurement research; 2. A common language and framework for exploring measurement problems is depicted for practitioners through the case study analysis; and 3. A connection between enterprise measurement and enterprise transformation is established to drive future transformation success.	
Whitaker, R. B. (2005) Value Stream Mapping and Earned Value Management: Two Perspectives on Value in Product Development, Cambridge, MA, Master's thesis, MIT and LAI.	(Whitaker, 2005) Download Link
The concepts of value and value stream are crucial to the philosophy of Lean, and a better understanding of how these concepts relate to product development (PD) is essential for the creation of a Lean PD strategy. This thesis focuses on value by looking at PD processes through two different value perspectives: Product Development Value Stream Mapping and Earned Value Management. Product Development Value Stream Maps (PDVSMs) were created for two different PD projects, and the tasks from the maps were analyzed for how they each create value. The official value measurement for the two projects, Earned Value Management System data, was analyzed and compared to the PDVSMs. This comparison of the two value perspectives proved valuable, as it showed that despite some misalignments, they are congruent. The comparison also highlighted several flaws in EVMS. A combined EVMS/PDVSM hybrid management tool is proposed and discussed.	

Paduano, R. (2001) Employing Activity Based Costing and Management Practices Within the Aerospace Industry: Sustaining the Drive for Lean, Cambridge, MA, Master's thesis, MIT and LAI.	(Paduano, 2001) Download Link
The case studies contained in the thesis have illustrated several aspects of Activity-based costing and management (ABCM) implementation within one of the largest facilities of the largest aerospace and defense sector company in the United States. What started as a tool to support the manufacturing environment by providing a link between manufacturing performance and financial benefits or losses, has the potential to migrate to a more strategic role, playing a central theme in the cost management strategy of the company. Barriers to implementation include poor upper management support, and continuous resistance in changing the culture of the employees affected by the implementations, especially those that belong to the finance and accounting departments. Enablers to widespread implementation are education, whereby the company's employees are exposed to the concepts of ABCM, understanding the benefits to be gained from widespread implementation, and communication. Continuous feedback provides a situation where the ABCM initiative does not get classified as another highly publicized and short-lived management optimization initiative. At the facility level, application of ABCM has shown an improvement in efficiency, and a reduction of the cost of quality.	

8.1.4 Risk management

This is an activity that makes the key program risks transparent, ensures that the understanding of risks is closely linked to the decision making process, strives to reduce uncertainty as much as possible, and account for residual uncertainty and risk with robust processes and systems.

Publication Title & Synopsis	Citation & Download Link
Oehmen, J. & Rebentisch, E. (2010) Risk Management in Lean PD. LAI Paper Series "Lean Product Development for Practitioners". Cambridge, MA, LAI and MIT.	(Oehmen and Rebentisch, 2010b) Download Link
The two core challenges of risk management are finding the optimum balance a) between the cost of carrying risks vs. the cost of mitigating risks and b) between a risk that is taken with a certain development project and the return that is expected from the project. This whitepaper summarizes the work conducted at LAI to-date on risk management. It contains a summary description of the ISO 31000 risk management process, a discussion of how these process steps can be adapted to development programs, an overview of risk management methods, as well as a review of past LAI research on risk management methods and processes, management of uncertainty, real options theory and portfolio-level risk management.	
Oehmen, J., Ben-Daya, M., Seering, W. & Al-Salamah, M. (2010) Risk Management in Product Design: Current State, Conceptual Model and Future Research. Proceedings of the ASME 2010 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2010	(Oehmen et al., 2010) Request at LAI
This publication expands the discussion of risk management methods currently discussed in the literature. It gives an overview of the product development oriented risk management literature along the seven process steps of 1. Communication and consultation, 2. Establishing the context, 3. Risk identification, 4. Risk analysis, 5. Risk evaluation, 6. Risk treatment and 7. Monitoring and review.	

Oehmen, J. & Ben-Daya, M. (2010) A Reference Model for Risk Management in Product Development Programs. Research Paper of the MIT-KFUPM Center of Clean Water and Energy. Cambridge and Dhahran, MIT and KFUPM.	(Oehmen and Ben-Daya, 2010) Request at LAI
This research report discusses in detail the risk management of complex engineering programs. It contains an overview of several risk management process frameworks, a detailed review of the ISO 31000 risk management guidelines, a discussion of how risk management can be executed in different phases of a program, and how these results can be integrated, as well as a detailed discussion of possible risks and mitigation measures for the different phases of a program.	
Oehmen, J., Seering, W.: Risk-Driven Design Processes – Balancing Efficiency with Resilience in Product Design. In: Birkhofer, H. (ed.) The Future of Design Methodology. Springer, London (2011)	(Oehmen and Seering, 2011) Request at LAI
In this book chapter, the authors argue that modern risk management should focus on achieving four major goals: 1. Create transparency regarding risks; 2. Make decisions based on risk knowledge; 3. Minimize uncertainty; and 4. Create a resilient organization. The chapter links those goals to classic risk management processes but ultimately argues that risk management and program management must become one overall process.	
The following documents are covered by the LAI Risk Management Whitepaper (see above)	
Wagner, C. (2007) Specification Risk Analysis: Avoiding Product Performance Deviations through an FMEA-based Method. Munich and Cambridge, Technical University of Munich and LAI.	(Wagner, 2007) Download Link
Meeting specifications during the design phase is crucial for the later success of a product. The research analyzes the characteristics of this design phase from a risk management perspective. It develops 24 requirements for a method to manage the risk of not achieving specifications, and based on these requirements, develops a risk management tool following the FMEA process. It identifies, assesses, and ranks product specifications that are challenging to achieve. It avoids product deficiencies and provides a systematic approach to develop appropriate mitigation measures. Thus, the method seeks to prevent time and cost-consuming changes at a later point.	
Madachy, R. & Valerdi, R. (2010) Automating Systems Engineering Risk Assessment. Proceedings of the 8th Conference on Systems Engineering Research, Hoboken, NJ, March 17-19 2010.	(Madachy and Valerdi, 2010) Download Link
This paper describes an automated expert system tool, Expert COSYSMO. It is a knowledge-based method for systems engineering risk assessment and mitigation. It is an extension of the COSYSMO cost model which supports PD project planning by identifying, categorizing, quantifying, and prioritizing system-level risks and project execution by providing mitigation advice. The knowledge base codifies the experience of seasoned systems engineering practitioners to identify and quantify risks, and provide risk mitigation advice for users to help develop their project-specific mitigation plans.	
Oehmen, J. (2005) Approaches to Crisis Prevention in Lean Product Development by High Performance Teams and through Risk Management. Munich and Cambridge, Technical University of Munich and LAI.	(Oehmen, 2005) Download Link
This thesis reviews the pre-ISO 31000 literature on PD risk management and develops a process framework similar to that introduced by ISO. The publication also contains an overview of PD-related risk management methods for every risk management process step.	

Browning, T. R., Deyst, J. J., Eppinger, S. D. & Daniel E. Whitney (2002) Adding Value in Product Development by Creating Information and Reducing Risk. IEEE Transactions on Engineering Management, 49, 443-458.	(Browning et al., 2002) Download Link
This publication develops the "risk value method" to link the probability distribution of performance outcomes in PD projects with the customer utility function. As design work proceeds, certainty increases surrounding the ability of the evolving product design (including its production process) to be the final design (i.e. technical performance risk decreases). The proposal is that making progress and adding customer value in PD equate with producing useful information that reduces performance risk. The risk value method integrates current approaches such as technical performance measure tracking charts and risk reduction profiles.	
Bresnahan, S. M. (2006) Understanding and Managing Uncertainty in Lean Aerospace Product Development. Master's Thesis. Cambridge, Massachusetts Institute of Technology.	(Bresnahan, 2006) Download Link
This thesis explores the role of uncertainty in lean product development, demonstrates the relationship between risk mitigation activities and the generation of customer value in the design and development process, and provides guidelines for completing these activities in a manner that reduces cycle time, assures quality, and makes the most efficient use of company resources. Product development teams that undertake aggressive and rigorous activities to identify uncertainties and risk ultimately encounter fewer problems and unplanned rework. These teams complete their project at an overall lower cost than the shortsighted teams who spend less to address uncertainty and risk, but meet greater problems later in the process. The thesis contains a list of recommended risk-related criteria for different stage gates.	
Mikaelian, T. (2009) An Integrated Real Options Framework for Model-based Identification and Valuation of Options under Uncertainty. Cambridge, Massachusetts Institute of Technology.	(Mikaelian, 2009) Download Link
This PhD thesis focuses on flexibility as an important means of managing uncertainties and leverages real options analysis that provides a theoretical foundation for quantifying the value of flexibility. Complex systems and enterprises, such as those typical in the aerospace industry, are subject to uncertainties that may lead to suboptimal performance or even catastrophic failures if unmanaged. This work introduces an Integrated Real options Framework (IRF) that supports holistic decision making under uncertainty by considering a spectrum of real options across an enterprise.	
Wirthlin, J. R., Seering, W. & Rebentisch, E. (2008) Understanding Enterprise Risk Across an Acquisition Portfolio: A Grounded Theory Approach. Seventh National Symposium on Space Systems Engineering & Risk Management, Los Angeles, CA, February 26-29, 2008.	(Wirthlin et al., 2008) Download Link
This publication analyses the current state of the art regarding portfolio level risk management in Air Force acquisition programs. Data collected from portfolio managers working at multiple levels of the system suggest that most are unable to articulate the risk carried by their portfolio of product development activities or what this means to them. However, the same interviews suggest they strongly desire this capability. From a review of the applicable literature in the areas of risk, product development (acquisition) and product portfolio management, portfolio-level risk applications are found to be sparse and ill-conceived. While portfolio leaders are expected to live within the resources available, they have few effective levers of control to influence portfolio performance.	

8.1.5 Project management

The activities include managing the execution of and transition between the different phases of the program, as well as the management of scope, time, budget and quality of the program (see Table 2 for a detailed summary).

There is no specific LAI work in project management as such. The following references are to two of the standard project management processes, the Project Management Institute (PMI) guidelines, as well as the PRINCE2 project management framework.

Publication Title & Synopsis	Citation & Download Link
Project Management Institute (2008): A guide to the project management body of knowledge (PMBOK guide), Drexel Hill, PA.	(PMI, 2008a) Link to PMI
The PMI guidelines address the following topics: Project Life Cycle and Organization; Project Management Processes; Project Integration Management; Project Scope Management; Project Time Management; Project Cost Management; Project Quality Management; Project HR Management; Project Communication Management; Project Risk Management; and Project Procurement Management.	
Office of Government Commerce (2009): Managing Successful Projects with PRINCE2, London, The Stationary Office.	(OGC, 2009) Link to OGC
The PRINCE2 project management guidelines contain the following topics: Project Management Principles; Project Management Themes; Starting up a project; Initiating a project; Directing a project; Controlling a stage; Managing stage boundaries; Managing product delivery; and Closing a project.	

8.1.6 Multi-project coordination

In addition to the challenges of managing a single project, program offices execute several projects in parallel, as well as contractors and suppliers on the different levels also usually have more than one project that they work on in parallel. This generates specific challenges, such as the allocation of resources, especially the staffing of the different projects in parallel along their specific life cycles.

Publication Title & Synopsis	Citation & Download Link
Herweg, G. M. & Pilon, K. E. (2001) System Dynamics Modeling for the Exploration of Manpower Project Staffing Decisions in the Context of a Multi-Project Enterprise, Master Thesis, LAI and Massachusetts Institute of Technology. and: Wright, M. R. (2003) Strategies for dealing with instabilities in a complex, multi-project product development system engineering environment, Master Thesis, LAI and Massachusetts Institute of Technology.	(Herweg and Pilon, 2001) Download Link (Wright, 2003) Download Link
Project decisions may be made on a project to project basis and often neglect to account for the complex interactions that exist between projects. Total workload and resource-usage are often not stable. In most environments, resources are limited, and thus have to be dynamically allocated according an ever-changing overall project situation. Often the current decision process results in a less than optimal return to the corporation. This return may not only be measured financially, but also in terms of organizational capability or intellectual capital. These works explore the effects of manpower decisions as well as other decisions in a multiple engineering project setting. Based on case studies, system dynamics models were developed to explore	

different options in regard to decision making in a multi-project environment. The recommendations are: 1. Short-term: 1.1 Limit overtime; 1.2 Keep project priorities stable; 1.3 Outsourcing; 2. Mid-term: 2.1 Develop detailed plans to ramp-up and ramp-down staffing levels at the begin and end of projects; 2.2 Cancel troubled projects early in their lifecycle; 3. Long-term: 3.1 Quality improvement; 3.2 Assess new projects also based on the intellectual capital that they generate; 3.3 Schedule buffer between projects

8.2 LAI's Insights: Enterprise Management

8.2.1 Developing intellectual capital

Companies and government organizations must provide incentives to their employees to develop deep technical knowledge and expertise in relevant areas. This includes encouraging and rewarding life-time careers as technical experts, for example through technology-oriented career towards senior engineers.

Publication Title & Synopsis	Citation & Download Link
Davidz, H. L. (2006) Enabling Systems Thinking to Accelerate the Development Senior Systems Engineers, Cambridge, MA, PhD Thesis, LAI and MIT.	(Davidz, 2006) Download Link
As engineering systems become more complex, the roles involved in developing and managing such systems also become more complex. Thus, there is increasing interest in educating and training engineering professionals to think more systemically. In particular, there is an increasing need to accelerate the development of senior systems engineers. In a field study, 205 interviews were conducted in 10 companies. Senior systems engineers were studied, as well as proven stellar systems thinkers interviewed. The best practices for industry to develop systems engineers include: 1. structure systems thinking interventions to emphasize experiential learning; 2. offer systems programs to teach systems skills and systems thinking; 3. filter and foster identified individual characteristics in systems organizations; 4. provide an environment supportive to the development of systems thinking; and 5. clearly communicate how strength of systems thinking is assessed.	
Herweg, G. M. & Pilon, K. E. (2001) System Dynamics Modeling for the Exploration of Manpower Project Staffing Decisions in the Context of a Multi-Project Enterprise, Master Thesis, LAI and Massachusetts Institute of Technology.	(Herweg and Pilon, 2001) Download Link
This work has already been discussed in section 8.1.6. It is also relevant to the development of intellectual capital: project experience is an important contributor to the skill development of the workforce. A successful long-term staffing strategy therefore has to balance direct project objectives (return on investment) with an overall, project-spanning goal of developing and maintaining a highly skilled workforce.	
Andrew, W. G. (2001) Do Modern Tools Utilized in the Design and Development of Modern Aircraft Counteract the Impact of Lost Intellectual Capital within the Aerospace Industry?, Cambridge, MA, Master Thesis, LAI and MIT.	(Andrew, 2001) Download Link
The new design experience of Post-World War II Aerospace Engineers was approximately 6-12 new design aircraft per career. In contrast, an aerospace engineer starting his career today may experience only one, maybe two new aircraft designs during their career. Anecdotal evidence has been published linking this trend to problems experienced in many recent aircraft programs. Counter arguments cite rapid advances in design, manufacturing and information technologies have compensated for some or all of declining experience base. An analysis of the program performance metrics revealed that the predecessor programs indeed outperformed the more recent programs. Examination of the case studies showed a strong correlation between intellectual capital metrics and the performance metrics for programs. This re-emphasizes the importance that must be placed on developing a skilled workforce.	
Siegel, L. R. (2004) Measuring and Managing Intellectual Capital in the U.S. Aerospace Industry, Cambridge, MA, Master Thesis, LAI and MIT.	(Siegel, 2004) Download Link
Intellectual capital consists of knowledge-based assets – including people, relationships, tools, and processes – that create value for a firm and its clients. In this research, a new conceptual framework is developed for understanding the role of	

intellectual capital in new product development. The framework develops a dynamic model of the three forms of intellectual capital – human capital, structural capital, and relational capital – and identifies mechanisms for knowledge transfer, organizational learning, and value creation. The framework is based on case studies of seven product development projects at different US aerospace firms. The thesis contains a self-assessment tool that managers can use to measure and assess the health of their intellectual capital base.	
Forseth, C. E. (2002) The Pursuit of Acquisition Intrapreneurs, Cambridge, MA, Research Report, LAI and MIT.	(Forseth, 2002) Download Link
This research focused on identifying Acquisition Intrapreneurs, viewed and defined for the purpose of this research as, individuals within the acquisition profession who take direct responsibility for turning ideas into products through assertive risk taking. A comprehensive survey was conducted and asked the acquisition workforce to respond to a number of statements regarding their current jobs, opportunities for advancement, future job interests and supervisor. Short term recommendations for increased innovation include specific funding and reporting for PCOs and engineers. A long term plan to develop future acquisition leaders, CGOs, is proposed through a framework for agile acquisition Jobs, Environment, Training and Support. This recommendation includes operational tours, an environment of failure-tolerant leadership, localized training through base-level Acquisition Center of Excellence offices and a rewards structure similar to the operational "W", or whiskey slots. The proposal tied the survey results and research theories together by providing a system to recognize, train, track and reward acquisition intrapreneurs.	
Lamb, C. M. T. (2009) Collaborative Systems Thinking: An exploration of the mechanisms enabling team systems thinking, Cambridge, MA, PhD thesis, LAI and MIT.	(Lamb, 2009) Download Link
Within the aerospace industry, an aging workforce places those with the most systems experience near retirement at a time when fewer new programs exist to provide systems experience to the incoming generation of aerospace engineers and leaders. It is therefore important to look at teams of aerospace engineers as a new unit of systems knowledge and thinking. By understanding more about how teams engage in collaborative systems thinking (CST), organizations can better determine which types of training and intervention will lead to greater exchanges of systems-level knowledge within teams. Based on numerous interviews, case studies and surveys, a model was developed to differentiate collaborative systems thinking (CST) teams from non-CST teams. These are 1. The right team balance between individual and consensus decision making; 2. The median number of past program experiences on a team; 3. Sufficient real-time group interactions; 4. An overall creative environment; and 5. A realistic program schedule.	

8.2.2 Building and transforming the program enterprise

Architecting the enterprise of both public (government) and private (companies) organizations that are involved in executing the program and creating stakeholder value. Transforming existing enterprises along an enterprise transformation roadmap to re-align them with stakeholder needs and optimize the value flow throughout the enterprise.

Publication Title & Synopsis	Citation & Download Link
Nightingale, D., Srinivasan, J.: Beyond the Lean Revolution: Achieving Successful and Sustainable Enterprise Transformation. AMACOM, New York (2011)	(Nightingale and Srinivasan, 2011) Order online
This book summarizes the past LAI research on enterprise transformation. Enterprise transformation begins with the big picture: What are the strategic objectives? How is the enterprise per forming against those objectives? How should it be? Who are the stakeholders and what do they value? Then it moves forward toward an audacious vision of the enterprise's future. This book provides a roadmap for achieving sustainable, bottom-line results, delivering value to stakeholders, and reaching that future vision. The main process steps that are covered are: ensure senior leadership commitment; assess the enterprise's current state; analyze stakeholder values; develop a future vision; and, create a plan for transformation. From inception to implementation, this book provides a framework for bridging the gap from mere change to genuine transformation.	
Nightingale, D., Stanke, A. & Bryan, F. T. (2008) Enterprise Strategic Analysis and Transformation (ESAT) - Version 2.0, Cambridge, MA, LAI Guide.	(Nightingale et al., 2008) Download Link
The Enterprise Strategic Analysis and Transformation (ESAT) methodology provides a means for the senior leadership team to understand their enterprise, create an actionable vision for the future, plan the transformation and govern the execution. The emphasis on enterprise thinking forces enterprises to transition from local lean efforts to Lean as an enterprise philosophy and is at the core of the ESAT transformation method. The Enterprise Strategic Analysis and Transformation (ESAT) methodology presented in this guide serves as an integrated, analytical framework for diagnosing and improving overall enterprise performance. The emphasis of ESAT on understanding the enterprise value streams, the value flow between key stakeholders and the enterprise, and interactions both within and across the enterprise, enables the identification of enterprise wastes and opportunities for improvement. Using the quantitative and qualitative data gathered as part of executing the ESAT, the enterprise leadership team can then create a future state vision, an actionable transformation plan, and put into place a governance structure to support and drive enterprise transformation. Equally important is the shared mental model that the senior leadership team creates during the execution of the ESAT, as it ensures that there is sustained leadership buy-in for the long transformation journey ahead.	
Stanke, A., Nightingale, D. & Bryan, F. T. (2008) Enterprise Strategic Analysis and Transformation (ESAT) - Facilitator’s Guide - Version 2.0, Cambridge, MA, LAI Guide.	(Stanke et al., 2008) Download Link
The ESAT facilitator’s guide is an accompanying document to the general ESAT guide discussed above. It provides an overview of the ESAT process, but it is assumed that all facilitators are comfortably familiar with the process as described in the ESAT Guide document and the ESAT KEE Modules (both instructional and facilitation). This	

document provides a general introduction to the facilitation techniques suggested for ESAT. It also provides a step-by-step outline for taking a team through the analysis. For each ESAT event/major time block, there is an overview and a detailed description in the following format. Throughout the guide are instructions for particular templates as well as examples of illustrative cases.	
Stanke, A. K. (2006) Creating High Performance Enterprises, PhD Thesis, LAI and Massachusetts Institute of Technology.	(Stanke, 2006) Download Link
There are a small number of exceptional programs that have managed to meet all of their commitments in terms of cost, schedule, and technical performance simultaneously. This work explores these programs on a case-by-case basis. Best practices from these programs are organized into a framework of factors that differentiate these high performing programs from the majority of others that struggle in the same environment. These factors are: 1. Distributed Leadership Action: 1.1 Boundary spanning activity across organizations in the enterprise; 1.2Developing and utilizing a social network; 1.3 Developing and sustaining extensive customer interactions; 1.4 Fostering and maintaining personal accountability of plans and outcomes; 2. Informal Structures: 2.1 Boundary spanning activity with the enterprise environment; 2.2 Encouragement for open information sharing; 2.3 Veteran core group to institutionalize behavior; 3. Formal Structures: 3.1 Balanced risk through work share and teaming arrangements; 3.2 Common contract structure; 3.3 Standardized program management practices (metrics and reporting system)	
Glazner, C. G. (2006) Enterprise Integration Strategies Across Virtual Extended Enterprise Networks: A Case Study of the F-35 Joint Strike Fighter Program Enterprise, Cambridge, MA, Master's thesis, LAI and MIT.	(Glazner, 2006) Download Link
Increasingly, integration efforts have moved beyond the boundaries of the core or focal enterprise serving as the prime contractor or system integrator to span the entire value chain, to form virtual extended enterprises. While integration offers many benefits to enterprises, a high degree of integration is not always desirable or advantageous in a limited duration virtual extended enterprise composed of autonomous companies. The objective of this research is to explore the extent to which a focal enterprise, such as a prime contractor or system integrator, should consider integration across its virtual extended enterprise, identify major barriers to integration, and define key enablers of integration overcoming these barriers. Analysis focuses on the extent of integration based on the characteristics of the virtual extended enterprise, such as the duration and scope of the program in question, product system architecture, the organizational architecture, and the external environment. In particular, three key conceptual dimensions of integration are developed and explored—technological integration, strategic integration, and organizational integration. This framework is applied in an in-depth case study of integration strategies on the virtual extended enterprise of the F-35 Joint Strike Fighter (JSF) Program. The knowledge gained from the case study is used to make recommendations for the development of integration strategies for future programs.	
Oehmen, J. & Rebentisch, E. (2010a) Compilation of Lean Now! Project Reports, Cambridge, MA, LAI Report.	(Oehmen and Rebentisch, 2010a) Download Link
The aim of Lean Now was to focus on the process interfaces between these enterprise stakeholders to eliminate barriers that impede progress. Any best practices developed would be institutionalized throughout the Air Force and the Department of Defense. The industry members of LAI agreed to help accelerate the government-industry transformation by donating lean Subject Matter Experts (SMEs) to mentor, train, and facilitate the lean events of each enterprise. This compilation contains project briefings	

illustrating the positive effects of Lean Now! in the following programs / processes: 1. F/A-22, 2. F-16, 3. Global Hawk, 4. Turbine Engine Development, and 5. Purchase Request Process. In addition, the compilation contains the Lean Now! workshop material.	
Jobo, R. S. (2003) Applying the Lessons of "Lean Now!" To Transform the US Aerospace Enterprise - A study guide for government lean transformation, Cambridge, MA, LAI Report.	(Jobo, 2003) Download Link
This research report summarizes the key learnings from the Lean Now initiative. From the observations of three Lean Now prototype programs, a common methodology for implementing lean can be developed. This methodology has three distinct phases: 1) Set-up Phase, 2) Planning Phase, 3) Execution and Follow-through. Within each phase are distinct steps that must occur in order for the lean initiative to be successful.	

8.2.3 Understanding the program enterprise

Assessing existing program enterprises to benchmark them against best practices and/or other program enterprises, as well as to uncover areas for improvement.

Publication Title & Synopsis	Citation & Download Link
LAI (2001) Lean Enterprise Self-Assessment Tool (LESAT) Version 1.0.	(LAI, 2001) Download Link
The Lean Enterprise Self-Assessment Tool helps organizations to determine their progress and maturity during a lean transformation. This document describes the LESAT tool and provides a structure and implementation reference for the self-assessment process. Extensive field-testing in more than 20 companies in both countries demonstrated the tool's utility, effectiveness and ease of use. It addresses the lean-related maturity of an organization in the following areas: Section I – Lean Transformation/Leadership: I.A Enterprise Strategic Planning (3 Lean practices); I.B Adopt Lean Paradigm (4 Lean practices); I.C Focus on the Value Stream (4 Lean practices); I.D Develop Lean Structure and Behavior (7 Lean practices); I.E Create and Refine Transformation Plan (3 Lean practices); I.F Implement Lean Initiatives (2 Lean practices); I.G Focus on Continuous Improvement (5 Lean practices); Section II – Life-Cycle Processes: II.A Business Acquisition and Program Management (4 Lean practices); II.B Requirements Definition (2 Lean practices); II.C Develop Product and Process (3 Lean practices); II.D Manage Supply Chain (3 Lean practices); II.E Produce Product (2 Lean practice); II.F Distribute and Service Product (4 Lean practices); Section III – Enabling Infrastructure: III.A Lean Organizational Enablers (5 Lean Practices); III.B Lean Process Enablers (3 Lean Practices)	
Nightingale, D. J. & Mize, J. H. (2001) Development of a Lean Enterprise Transformation Maturity Model. Information, Knowledge, Systems Management, 3, 15-30.	(Nightingale and Mize, 2001) Request at LAI
This journal publication provides background information to the Lean Enterprise Self-Assessment Tool (LESAT). It explains its integration into an enterprise transformation process, discusses a number of other approaches to organizational assessment, explains the rationale behind the design of the LESAT tool and gives a brief introduction to the tool itself..	
Ferdowsi, B. & Stanke, A. (2002) F-16 Case Study Report - Lean Effects on Aerospace Programs (LEAP) Project, Cambridge, MA, LAI Report.	(Ferdowsi and Stanke, 2002) Request at LAI
This case study describes the F-16 Enterprise. The continuous, evolutionary development strategy of the F-16 has substantially increased the functionality of the	

system while the dimensions of the airframe have remained constant. This report follows the F-16 journey of improvement over the last decade. Since an increase in focus on cost and quality in the early 1990s, there has been gradual but continuous progress along this journey. Most remarkable are some of the more recent changes, following the implementation of lean principles and practices across the program. there has been less than three percent increase in the price of the Contractor Furnished Equipment portion of the aircraft in the last ten years. Not only has the price been kept nearly constant, but Lockheed Martin also have a record of 100+ months of consecutive on-time deliveries. They have developed and produced over 100 different type versions of this aircraft (i.e. tailored configurations) for their various customers. All of these achievements have been made despite fluctuating demand heavily contingent on international sales and a substantial drop in production rate from 200+ to 24 aircraft per year.	
Ferdowsi, B. & Haggerty, A. (2002) 737 Fuselage Case Study Report - Lean Effects on Aerospace Programs (LEAP) Project, Cambridge, MA, LAI Report.	(Ferdowsi and Haggerty, 2002) Download Link
This case study describes the Boeing 737 "Next Generation" Enterprise. The plant ramped up production from 10 to 28 planes per month, which in itself is remarkable, but in this time, several other lean principles were set in motion, leading to great improvements. For example, flow time in the factory was reduced by 21 percent, while creating capacity to add work content from the Boeing final assembly plant in Renton, WA. Furthermore from 1998 to 2000, labor hours per unit were reduced by nearly 50 percent. Unit cost was reduced by 25 percent over the same period.	
Davidz, H. & Nightingale, D. (2002) AMRAAM Case Study Report - Lean Effects on Aerospace Programs (LEAP) Project, Cambridge, MA, LAI Report.	(Davidz and Nightingale, 2002) Request at LAI
This case study describes the production of the AMRAAM-120. One of the most interesting observations is the cooperative relationship Raytheon has with their U.S. Government customer. The accomplishments of the AMRAAM program were made possible by using lean methods to develop an improved, trusting relationship with their U.S. Government customer. With strong, insightful leadership from both the contractor and the government, this cooperation enabled an even higher level of lean and even more cost reduction. The Agile program and Raytheon Six Sigma have created a culture where the six sigma/lean tools are institutionalized. Strong leadership at all levels has provided the motivation and support for continued change. People are empowered at all levels, and there is teamwork across the organization.	
Derleth, J., Hitchings, S. & Rebentisch, E. (2003) Atlas Case Study Report - Lean Effects on Aerospace Programs (LEAP) Project, Cambridge, MA, LAI Report.	(Derleth et al., 2003) Request at LAI
This case study describes the Atlas expendable launch vehicle. Along with its successful launch performance, the Atlas program has also achieved significant business and operating success, which this case study attempts to document. Due to different market factors, Lockheed Martin not only needed to reduce its costs, but also to increase its capacity to produce Atlas launchers, as well as a 50% reduction in order-to-delivery cycle time. Lockheed Martin achieved these goals by implementing lean principles that allowed them to reduce cycle time, man hours needed for assembly, overhead costs, and other forms of waste.	
Stanke, A. K. (2006) Creating High Performance Enterprises, PhD Thesis, LAI and Massachusetts Institute of Technology.	(Stanke, 2006) Download Link
This thesis contains three relevant case studies: The F/A-18E/F case study on the	

robust enterprise, the JDAM case study on the agile enterprise, as well as the case study on the X-35 as an example for a flexible enterprise (see section 0 for more detail on this publication).	
Cowap, S. A. (1998) Economic Incentives in Aerospace Weapon Systems Procurement, Master Thesis, LAI and Massachusetts Institute of Technology.	(Cowap, 1998) Download Link
A number of incentive-related best practices are benchmarked in this thesis. It contains case studies on two Air Force ammunition programs, C-130J case study, as well as a case study on the C-17 program. Please refer to section **Error! Reference source not found.** for more details.	
Labedz, C. S. & Harvey, R. K. (2006) Letterkenny Army Depot: Finance Innovations Support Lean Six Sigma Success.	(Labedz and Harvey, 2006) Download Link
As a result of significant dollar savings to the Army and U.S. taxpayers, Letterkenny Army Depot received widespread public recognition in 2005. The depot received a public sector Shingo Prize for applying Lean principles and tools to its PATRIOT missile system recapitalization program. While Letterkenny was Leaning its production systems, the depot implemented two innovative and effective financial incentive systems: one to reward employees, the other to reward customers. The reward systems were innovative because they occurred in a not-for-profit organization and effective because they motivated customers, employees, and unions to embrace Lean. The case describes the organizational conditions leading to these innovations and the responses to them among its customers, unions and headquarters.	

8.2.4 Learning and improving in the program enterprise

Successfully managing continuous improvement and organizational change in complex enterprises.

Publication Title & Synopsis	Citation & Download Link
Bozdogan, K. (2010) Towards An Integration Of The Lean Enterprise System, Total Quality Management, Six Sigma And Related Enterprise Process Improvement Methods, Cambridge, MA, MIT LAI / ESD Working Paper (ESD-WP-2010-05), scheduled for publication in Encyclopedia of Aerospace Engineering.	(Bozdogan, 2010) Download Link
In recent years, a growing number of firms in many industries have adopted Lean Thinking, Six Sigma and related enterprise process improvement initiatives to achieve continuous performance improvement and, often, to bring about enterprise-wide change and transformation. This paper presents a critical comparative review of these initiatives to identify the similarities and differences among them, highlight how they relate to each other, and assess their strengths and weaknesses. The paper strives to provide an improved understanding of these initiatives to enable enterprises develop better-informed change and transformation strategies. More specifically, the paper focuses on Lean Thinking, Total Quality Management (TQM), Six Sigma, Theory of Constraints (TOM), Agile Manufacturing, and Business Process Reengineering. A main conclusion of the paper is that Lean Thinking provides an overarching intellectual architecture for the various systemic change initiatives, wherein they share common roots, augment each other in significant ways, and generally comprise mutually-complementary approaches. The various differences among them are dwarfed by their common characteristics. Taken together, under the overall umbrella of Lean Thinking, they are rapidly merging into a unified framework for bringing about fundamental enterprise-wide change.	

Roth, G. (2008) The Order and Chaos of the Learning Organization. In Cummings, T. (Ed.) Handbook of Organization Development. Newbury, CA, Sage.	(Roth, 2008) Request at LAI
This book chapter summarizes the most important perspectives on organizational learning: 1. Organizational learning as accumulated experience; 2. Organizational learning as adaptation to environmental changes; 3. Organizational learning as assumption sharing; and 4. Organizational learning as developing the knowledge base. The different concepts are integrated with the broader field of management research into into a framework of the Learning Organization that integrates diverse concepts such as team organization, management by objectives, strategic planning, value chain management, quality management , core competencies and cultural change. The goal is to develop an organization that continually expands its capacity to create its own future.	
Roth, G. (2006) Distributing Leadership Practices for Lean Transformation. Reflections - The SoL Journal on Knowledge, Learning, and Change, 7, 15-31	(Roth, 2006) Request at LAI
Many organizations have achieved impressive results in various aspects of their business through lean transformation. Few firms, however, sustain those initial results, and many struggle to bring the results down to a bottom-line impact. This article links research literature on change management with lean case studies and presents a form of distributed leadership that facilitates lean transformation. Distributing leadership practices is one of five capabilities identified for successful lean enterprise change: 1. Rethinking organizational boundaries; 2. Installing innovation sets; 3. Pushing and pulling change; 4. Seeking growth opportunities; and 5. Distributing leadership practices	
Deardorff, S. J. K. (2003) Institutionalizing Change in Aerospace Process and Product Settings, Cambridge, MA, Master's thesis, MIT and LAI.	(Deardorff, 2003) Download Link
This thesis is an examination of the methods used to introduce and sustain change to help answer the reasons why some organizations are successful at adapting and some are not. In order to affect beneficial change, strategies to promote transformations must recognize the political, economic, and social issues, as well as the capabilities of the organizations. The research is based on four separate case studies of organizations that produce, or manage the delivery of, a technically complex good or service. More commitment from lower level leadership and a wider availability of best practice documentation corresponds to less regression to former practices. More formal training led to wider diffusion of change, but availability of documentation did not correspond to greater diffusion or adoption of new practices. However, better availability of documentation did correspond to less regression. The strongest defenses against regression were not supporting the old process or making permanent or semi-permanent physical changes to the work area. The recommendations include using small, organic change offices in business areas that do not have a history of mature change practices to use as models, setting aside a percentage of realized savings for human resources investment, and time-in-grade provisions for management positions to allow for greater continuity.	
Cohen, J. L. (2005) United States Air Force Air Logistics Centers: Lean Enterprise Transformation and Associated Capabilities, Cambridge, MA, Master's thesis, MIT and LAI	(Cohen, 2005) Download Link
Lean enterprise transformation entails a complementary set of initiatives and efforts executed over a substantial period of time, in a consistent and coordinated manner, at all levels of the enterprise. It builds upon ordinary organizational change in that a broader set of people and functions will be affected, and non-traditional approaches and mental models will continue to be exercised. Between 2003 and 2005, three US Air Force Air Logistics Centers (ALCs) initiated lean enterprise transformation efforts. A set	

of 12 lean enterprise change capabilities is proposed: 1. A leadership team with a shared mental model; 2. Planning and implementation process; 3. Balanced and cascading system of metrics; 4. Standardized processes and a team to track them; 5. Compensation and reward system; 6. Developing and deploying vision and mission; 7. Communication and public relations abilities; 8. Change management; 9. Cadre of change agents; 10. Context for local experimentation; 11. Continued learning and self-renewal; and 12. Training and education.	
Shoepe, T. V. (2006) In Pursuit of Understanding Lean Transformation - Capturing Local Change Journeys in a DoD Field Environment, Cambridge, MA, LAI Research Paper.	(Shoepe, 2006) Download Link
Guided by the Secretary of Defense, both the USAF and USN have adopted “lean” principles as a compass to help guide the transformational journeys of their acquisition programs. This study describes two of the US Air Force and US Navy enterprise-level continuous process improvement programs and the ways in which each contribute to local results in a field case setting. Additionally, this study tests the applicability of ongoing LAI lean enterprise change theory in the context of a DoD environment. Three noteworthy results were discovered: 1. Both the Navy and USAF have been using lean principles for years. However, they have traditionally been limited to the manufacturing floors and USAF Air Logistics Centers. 2. On the foundation of these successes, both organizations are placing the strategic leadership, vision, infrastructure, and processes in place to proliferate continuous improvement throughout their enterprises. 3. With minor tailoring, the ongoing change management theory development at LAI is applicable to evaluating enterprise change in the context of a DoD field case.	
Hemann, J. M. (2005) Improving Complex Enterprises with System Models, Cambridge, MA, Master's thesis, MIT and LAI.	(Hemann, 2005) Download Link
Air Force sustainment operations are the focus of an intensive internal effort to improve performance and reduce costs. Past improvement initiatives have often failed to produce the intended results. Exploratory research was conducted at an Air Logistics Center to study how improvements are executed. Two conclusions are drawn from this research. The first is that changing sustainment operations is a problem of high dynamic and behavioral complexity. The second conclusion is that system models are well suited to coordinating change because they provide insight into how a complicated system can be managed and improved. Three key findings support these conclusions. First, there is significant correlation between categories of unavailable F-16 aircraft such that reductions in one category are associated with increases in another. Second, an analysis of change efforts in two parts of the ALC shows that systemic influences, such as the inability to reinvest in improvements, are hindering change initiatives in one part of the ALC. The third finding is that a model of sustainment operations suggests that independent improvement initiatives are outperformed by coordinated efforts driven with an understanding of systemic interactions.	

8.3 LAI's Insights: Scoping, planning & contracting

During Scoping, Planning & Contracting, the user needs are translated into a legal contract between the program office and the main contractor. As part of this, the life cycle strategy for the entire program is planned and codified, spanning system development, technology transition, operational use and sustainment, as well as future technology refresh and ultimate system disposal. This step includes the following activities:

8.3.1 Definition of stakeholder needs and requirements

The stakeholders in large programs are numerous and varied, and so are the resulting needs. Stakeholders from different areas – government, congress, users, general public, contractors etc. – and different levels of the hierarchy – top management to shop floor – have to be taken into account. This requires a sophisticated process for eliciting and aligning these diverse needs.

Publication Title & Synopsis	Citation & Download Link
Rebentisch, E. (1996) Preliminary Observations on Program Instability, Cambridge, MA, LAI Whitepaper LEAN 96-03.	(Rebentisch, 1996) Download Link
This white paper provides details about research on program instability. Its objective is to discuss high-level findings detailing: 1) the relative contribution of different factors to a program's overall instability; 2) the cost impact of program instability on acquisition programs; and 3) some strategies recommended by program managers for overcoming and/or mitigating the negative effects of program instability on their programs. The government managers of military acquisition programs rated annual budget or production rate changes, changes in requirements, and technical difficulties as the three top contributors, respectively, to program instability. When asked to partition actual variance in their program's planned cost and schedule to each of these factors, it was found that the combined effects of unplanned budget and requirement changes accounted for 5.2% annual cost growth and 20% total program schedule slip. Program management practices involving the integration of stakeholders from throughout the value chain into the decision making process were rated the most effective at avoiding program instability. The use of advanced information technologies was rated the most effective at mitigating the negative impact of program instability.	
Dare, R. E. (2003) Stakeholder Collaboration in Air Force Acquisition: Adaptive Design Using System Representations. Cambridge, MA, PhD thesis, LAI and MIT.	(Dare, 2003) Download Link
Air Force development of new or evolutionary weapon systems is a complex endeavor due to the involvement of many stakeholders and the presence of considerable uncertainty in the acquisition environment. The ability to adapt a weapon system while it is still being designed affords a means to respond to this complexity. Eight case studies were conducted on Air Force development programs. Data were collected on collaborative practices and patterns of adaptability demonstrated during design. The research placed an emphasis on usage of "system representations" such as prototypes and beta software releases that acted as a form of boundary object to facilitate knowledge sharing across organizational boundaries. This research indicates that the pressing need for Air Force programs to be able to adapt in today's uncertain acquisition environment can be addressed to a significant degree through the usage of effective system representations in conjunction with supporting patterns of	

stakeholder interaction. Specific recommendations for Air Force acquisition policy makers and practitioners are: 1. Make system representations and adaptability part of acquisition planning; 2. Involve the operational user in the design phase; 3. Create effective system representations; 4. Make effective use of system representations; and 5. Create a “zone of novelty”, i.e. a mix of flexibility and structure for the program.	
Wirthlin, J. R. (2000) Best Practices in User Needs / Requirements Generation, Cambridge, MA, Master’s thesis, LAI and MIT.	(Wirthlin, 2000) Download Link
This research develops a process framework for the early phases of product development, from the initial recognition of a customer need to the decision launch a development program. The framework focuses on the development of the requirements that are needed to decide the business case. Detailed case studies of military and commercial organizations, as well as within the Air Force, were conducted and best practices in the early product development phases identified. These include identification of requirements, screening of requirements, concept development, business case development, as well as organizational and business enablers. Also included is an instrument to assess the maturity of an organization’s early phases of its product development process.	
Walton, M. A. (1999) Identifying the Impact of Modeling and Simulation in the Generation of System Level Requirements, Cambridge, MA, Master's thesis, LAI and MIT.	(Walton, 1999) Download Link
Requirements generation is an influential time in the evolution of the program. It allocates 70% of the life-cycle cost of a program and is responsible for a large percentage of the system errors and cost overruns. This research develops a framework to describe the current state of requirements generation and then focuses on the use of modeling and simulation within the process. It is shown that although modeling and simulation tools are being used extensively in requirements generation in many programs throughout the DoD, their effectiveness is largely undocumented and areas of high leverage are unknown. Research results also indicate that a more effective use of modeling and simulation within requirements generation could be achieved with increased tool interoperability and easier tool validation and verification. Finally, the ability to perform more iterations early and the benefits as a boundary-spanning tool for communication are discussed as the two main benefits of modeling and simulation.	
Gillespie, D. M. (2009) Mission Emphasis and the Determination of Needs for New Weapon Systems, Cambridge, MA, PhD thesis, LAI and MIT.	(Gillespie, 2009) Download Link
Efforts to understand the determination of needs of new weapon systems must take into account inputs and actions beyond the formally documented requirements generation process. This study analyzes three recent historical cases of fighter aircraft development to identify decisions made independently from the documented requirements process, about the need for new systems. The primary inputs to those decisions are identified, and a qualitative model for understanding the undocumented inputs, and their role in determining weapon system needs, is presented. By analyzing data across the cases, which span a period of significant change in fighter design, the concept of a Dominant Mission Emphasis (DME) is introduced. The DME is defined as that mission which receives the most emphasis from the majority of participants in the needs determination process, and which the majority of other missions support, either directly or indirectly. Cues are identified which suggest the need to re-examine the DME. The strength of a DME can be measured by qualitative and quantitative indicators, including such things as verbal statements, military doctrine, intellectual and academic writings, organization within the military, resources committed, and	

promotion decisions.	
Cameron, B. G., Crawley, E. F., Loureiro, G. & Rebentisch, E. S. (2008) Value flowmapping: Using networks to inform stakeholder analysis. Acta Astronautica, 62.	(Cameron et al., 2008) Request at LAI
Stakeholder theory has garnered significant interest from the corporate community, but has proved difficult to apply to large government programs. A detailed value flow exercise was conducted to identify the value delivery mechanisms among stakeholders for the current Vision for Space Exploration. We propose a method for capturing stakeholder needs that explicitly recognizes the outcomes required of the value creating organization. The captured stakeholder needs are then translated into input–output models for each stakeholder, which are then aggregated into a network model. Analysis of this network suggests that benefits are infrequently linked to the root provider of value. Furthermore, it is noted that requirements should not only be written to influence the organization's outputs, but also to influence the propagation of benefit further along the value chain. A number of future applications of this model to systems architecture and requirement analysis are discussed.	
Loureiro, G., Crawley, E., Catanzaro, S. & Rebentisch, E. (2006) From Value to Architecture - Ranking the Objectives of Space Exploration (IAC-06-D1.4.2). Proceedings of the International Astronautical Congress (IAC 2006), Valencia, Spain, 2 - 6 October 2006.	(Loureiro et al., 2006) Request at LAI
This paper describes and discusses a process for identifying and ranking the objectives of space exploration. Objectives were generated and structured. Initial objectives were then classified as stakeholder intent objectives, outcomes to stakeholders and assets to be provided by the exploration enterprise to stakeholders. Assets derived objectives at lower level and these were organized into disjoint sets. Objectives were then related to stakeholder groups. Objectives within each stakeholder group were ranked using the Kano model. Architectures were, then, ranked based on their relationship to the ranked objectives. Architectures were ranked, separately, per stakeholder value, per cost, per risk and per policy robustness. There was no one overall metrics composed by each stakeholder group value, cost, risk and policy robustness. The paper exemplifies the process with the actual objectives, their resulting ranking per stakeholder group and the use of the ranked objectives to rank candidate architectures generated. The paper discusses the preferred architectures per stakeholder group and concludes with a critical analysis of the process.	
Ippolito, B. J. (2000) Identifying Lean Practices for Deriving Software Requirements, Cambridge, MA, Master's thesis, LAI and MIT.	(Ippolito, 2000) Download Link
Based on detailed case studies, this research analysis the process for deriving software requirements from the standpoint of lean management. Ten aerospace software upgrades were analyzed at both an enterprise level and an organizational level to identify the presence of Lean practices. At the enterprise level, metrics typically used to measure enterprise performance (Flow Time, Stakeholder Satisfaction, Quality Yield, and Resource Utilization) were found to be appropriate for the software requirement process but not adequately implemented. An organizational analysis observed five of the twelve Lean practices as effectively implemented. These are 1. Implement integrated product and process development; 2. Maximize stability in a changing environment; 3. Assure seamless information flow; 4. Develop relationship based on mutual trust and commitment; and 5. Continuous focus on the customer. The research also identified opportunities to implement three more Lean practices: 1. Identify and optimize enterprise flow; 2. Optimize capability and utilization of people; and 3. Make decisions at the lowest possible level.	

Downen, T. D. (2005) A Multi-Attribute Value Assessment Method for the Early Product Development Phase With Application to the Business Airplane Industry, Cambridge, MA, PhD Thesis, MIT and LAI.	(Downen, 2005) Download Link
The early phase of product development is critical to the success of enterprises. In addition, it has been argued that the concept of consumer value is central to effective product development. In this research, a new product value assessment method is established for the fuzzy front-end of business airplane development. A recently-developed multi-attribute value method, based on Taguchi's loss function approach to quality assessment, is modified and extended in this study and applied for the first time to the domain of business aviation. A comprehensive 40-year historical product database is developed for use in testing and evaluating the method, referred to as the Relative Value Index (RVI), enabling the scope of value method appraisal to be expanded to an industry-wide examination over a significant time span. This methodology is a useful advance in the methods to extract objective findings from historical industry market activities. Marking the first independent review of the loss function-based value method, this study finds that the Relative Value Index is superior to existing value methods at retaining simplicity of implementation and minimal data requirements while maintaining a firm grounding in economics and consumer choice theory.	
Dickerson, C. & Valerdi, R. (2010) Using Relational Model Transformations to Reduce Complexity in SoS Requirements Traceability: Preliminary Investigation, Loughborough, UK, 5th IEEE International Conference on Systems of Systems Engineering, June 2010.	(Dickerson and Valerdi, 2010) Request at LAI
The principles and methods of Model Driven Architecture are applied to the problem of requirements traceability for a System of Systems (SoS). Model transformations of operational threads are used to reduce the complexity of modeling mission requirements and their flow into the architecture of the SoS. The allocation of requirements to operational mission threads (OMTs) rather than to individual systems reduces the complexity of the requirements tracing. Relational transformations provide a mathematically based formalism for model transformations that permit precise computation of the transformation of operational threads into threads of systems allocated from the SoS. Connectivity requirements for the SoS are also exposed in this way and the number of permissible system threads are seen to correspond directly to the number of permissible transformations. The principles and methods are illustrated by an elementary case study for sensor fusion.	
Matty, D.: Stakeholder Salience Influence on Bureaucratic Program Enterprise Value Creation. Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA (2010)	(Matty, 2010) Download Link
The government acquisition system has been studied extensively. Applying traditional system engineering methods have not improved performance, but developed a highly-complex bureaucracy that is viewed as inflexible, unscalable, unreliable, and (recently) unsustainable. With this seemingly intractable challenge, this work uses the synergy of integrating approaches based on engineering, management, and social sciences to develop a new framework to help understand the policy resistance of many previous unsuccessful initiatives. This research seeks to develop a dynamic enterprise engineering system framework using case study methodology to integrate three widely adopted but disparate frameworks by evaluating the influence relationships. Informed by the enterprise architecture, this new framework seeks to incorporate stakeholder salience and its dynamic influence on value creation as an endogenous factor in the context of the bureaucratic program enterprise of DOD acquisition. This work not only proposes an intermediate level theory but also provides insights for policy implications.	

8.3.2 Managing trade-offs

During the specification of the final requirements, conflicting requirements have to be traded against each other. This includes for example trade-offs regarding cost, schedule, performance and risk requirements. The management of trade-offs must also include re-visiting and re-negotiating requirements where necessary, in order to assure that the baseline requirements are realistic.

Publication Title & Synopsis	Citation & Download Link
Derleth, J. E. (2003) Multi-Attribute Tradespace Exploration and its Application to Evolutionary Acquisition, Cambridge, MA, Master's thesis, LAI and MIT.	(Derleth, 2003) Download Link
The concept of Evolutionary Acquisition (EA) provides many challenges to a system engineer, especially regarding the definition and trading-off of requirements. Multi-Attribute Tradespace Exploration (MATE) is a tool that can provide some focus on a project in EA. MATE is a method of developing models to simulate the product user's preferences for the attributes of a design. Once these preferences are well known, they can be used to guide the design choice. The design choice is further guided by the creation of system level computer models that represent the design choices available to the engineer. These choices are then varied systematically to create a "tradespace" of possible designs. This tradespace exhaustively enumerates all of the possible design choices for the engineer. Then, through the preference models previously developed, each possible design is ranked in order of user utility and cost. The result can be graphed, giving a visual representation of the utility and cost of literally thousands of architectures in a single glance. This research is based on a case study of the Small Diameter Bomb (SDB) and shows that MATE is a useful tool for a systems engineer working on an EA system. There are several benefits to the use of MATE in EA, including: 1. a better understanding of the end user's desires and requirements for the system; 2. the ability to optimize the system for the first evolution; 3. the possibility of understanding what will become optimal in later evolutions; 4. quick redesign time if circumstances or preferences change; and 5. further insight into systems level considerations.	
Spaulding, T. J. (2003) Tools for Evolutionary Acquisition: A Study of Multi-Attribute Tradespace Exploration (MATE) Applied to the Space Based Radar, Cambridge, MA, Master's thesis, LAI and MIT.	(Spaulding, 2003) Download Link
In this research, the Multi-Attribute Tradespace Exploration (MATE) process was applied to the Space Based Radar (SBR), a space system under study by the United States Air Force. A system-level model of possible SBR architectures was created using data and analysis from previous high-level studies. Competing designs were evaluated through MATE's universal utility metric. The MATE model was qualitatively compared against a high-level design study and MATE's advantages were noted, specifically its ability to trace modeling assumptions and present a holistic view of the space of competing designs. A quantitative comparison revealed significant differences between MATE's recommended system design and that of the comparison high-level study. The potential for a simplification of the MATE method was explored through the use of several approximations to revealed user preferences. It was shown that while a linear or subjective approximation to utility curves resulted in excessive errors, approximation to weighting relationships did not. Finally, MATE's potential applicability to the Air Force acquisition process was studied. In general MATE was shown to be useful to any acquisition effort that derives its benefit from a networked approach and is of sufficient technical complexity as to make tradeoff decisions	

opaque to casual analysis. Specifically, MATE was shown to be useful in the analysis of alternatives process as well as an aid to early milestone sourcing decisions.	
Ross, A. M. (2003) Multi-Attribute Tradespace Exploration with Concurrent Design as a Value-Centric Framework for Space System Architecture and Design, Cambridge, MA, Master's thesis, LAI and MIT.	(Ross, 2003) Download Link
This research investigates incorporating decision theory methods into the early design processes to streamline communication of wants and needs among stakeholders and between levels of design. Communication channeled through formal utility interviews and analysis enables engineers to better understand the key drivers for the system and allows for a broad and more thorough exploration of the design tradespace. Multi-Attribute Tradespace Exploration (MATE), an evolving process incorporating decision theory into model and simulation-based design, has been applied to several space system projects. The conclusions of these studies indicate that this process can improve the quality of communication to more quickly resolve project ambiguity, and enable the engineer to discover better value designs for multiple stakeholders. MATE is also being integrated into a concurrent design environment to facilitate the transfer of knowledge of important drivers into higher fidelity design phases. MATE with Concurrent Design (MATE-CON) couples decision makers more closely to the design, and most importantly, maintains their presence between formal reviews.	
Tang, V. (2006) Corporate Decision Analysis: An Engineering Approach, Cambridge, MA, PhD thesis, LAI and MIT.	(Tang, 2006) Download Link
This thesis explores corporate decisions and their solutions under uncertainty using engineering methods. The proposition is that as in an engineering system, corporate problems and their potential solutions deal with the behavior of systems. Since systems can be studied with experiments, this research uses Design of Experiments (DOE) to understand the behavior of systems within which decisions are made and to estimate the consequences of candidate decisions as scenarios To test this engineering approach to decision analysis, four experiments are performed. The first two are a set of simulations using a company surrogate. Using a progression of experiments, two major corporate decisions are simulated. Simulation data show that there is support for the validity of the decision analysis method. Then two in situ experiments are performed: with a manufacturing company and with a technology services company. Findings from these company experiments also support the validity and efficacy of the decision analysis method.	

8.3.3 Cost estimation & life cycle costing

Before a budget is allocated, the resource requirements in term of cost, schedule, manpower, facilities and other resources has to be forecasted. This involves a probability-based assessment of these resources so an informed decision can be made in the following step regarding the type and content of the contract.

Publication Title & Synopsis	Citation & Download Link
Valerdi, R. (2005) The Constructive Systems Engineering Cost Model (COSYSMO), Los Angeles, CA, PhD Thesis, USC.	(Valerdi, 2005) Download Link
This dissertation presents a parametric model that can help people reason about their decisions related to systems engineering. COSYSMO, the Constructive Systems Engineering Cost Model, is an “open” model that contains eighteen parameters: four size drivers and fourteen effort multipliers. It is built on a framework similar to its well-known predecessor, COCOMO II, and integrates accepted systems engineering standards to define its scope. The four size drivers are: Number of System	

Requirements, Number of Major Interfaces, Number of Critical Algorithms, and Number of Operational Scenarios. The fourteen effort multipliers are: Requirements understanding, Architecture understanding, Level of service requirements, Migration complexity, Technology risk, Documentation to match life cycle needs, Number and diversity of platforms, Number of recursive levels in the design, Stakeholder team cohesion, Personnel or team capability, Personnel experience or continuity, Process capability, Multisite coordination, and Tool support.	
Valerdi, R., Rieff, J. E. & Wang, G. (2007) Lessons Learned From Industrial Validation of COSYSMO, San Diego, CA, 17th INCOSE Symposium, June 2007.	(Valerdi et al., 2007) Download Link
The development of COSYSMO has been an ongoing collaboration between industry, government, and academia since 2001. Now that the development phase of the model is completed we take a retrospective view of lessons learned during the ongoing validation phase of the model and present new lessons learned that should help cost model developers, academic researchers, and practitioners develop and validate similar approaches. These lessons include the need for more specific counting rules, an approach to account for reuse in systems engineering, and strategies for model adoption in organizations.	
Valerdi, R. (2010) Heuristics for Systems Engineering Cost Estimation. IEEE Systems Journal.	(Valerdi, 2010) Download Link
This paper provides thirty one heuristics that have been inspired by the development and application of a systems engineering cost estimation model. The objective of this paper is to present such heuristics in a simple manner so that they can benefit systems engineering researchers and practitioners. They fall into the four categories of model development heuristics, model calibration heuristics, model usage heuristics and estimation heuristics.	
Czerwonka, S. P. (2000) Avionics Life-Cycle Forecasting Model, Cambridge, MA, Master's thesis, MIT and LAI.	(Czerwonka, 2000) Download Link
Sustaining aging aircraft fleets is a major challenge. Avionics are of particular concern due to rising problems with reliability and obsolescence as these systems age. If these problems are not addressed before an avionics component reaches the end of its life cycle, aircraft availability can suffer and sustainment costs can rise dramatically. This thesis presents a computational model that analyzes component performance metrics to forecast the time that an avionics component will reach the end of its life cycle. The purpose of the model is to provide aircraft program managers with a means of identifying critical components in advance of the onset of aging difficulties so as to allow corrective measures to be taken which can prevent unnecessary hardships.	

8.3.4 Incentive alignment, contract negotiation & conclusion

Contracting under large program risks is a very challenging task. Based on the cost (and other resources) probability distributions, an adequate way of sharing risk (cost overrun relative to baseline) and profit (cost savings relative to baseline) has to be developed. This should allocate the responsibility for carrying risk consequences according the responsibility for the risk sources, or create incentives to accept external risks. An important part of this process is understanding and aligning incentives between the program office and the contractors, as well as between contractor and its suppliers. Incentives must include guidelines on how to share benefits from local and enterprise-level improvements, improvements strategies, as well as guidelines for recovering stressed relationships.

Publication Title & Synopsis	Citation & Download Link
Dorey, S.: Enhancing cost realism through risk-driven contracting: Designing incentive fees based on probabilistic cost estimates. Research report, Lean Advancement Initiative, Massachusetts Institute of Technology, March 2011 (2011).	(Dorey, 2011) Request at LAI
A risk-driven contract structure is proposed to enhance the cost realism of competitive proposals for the Engineering and Manufacturing Development (EMD) phase of the acquisition lifecycle. An economic theory framework is employed to discuss how the cost-plus contracts typically used during this phase have inadvertently motivated contractors to provide optimistic cost estimates in an attempt to win competitive source selections. By directly mapping probabilistic cost estimates to profit distributions, risk-driven contracts offer a structured method to impose more cost risk sharing on contractors during EMD. Holding contractors accountable for their cost estimates and cost performance should enhance the realism of their cost proposals and ultimately reduce the cost growth that continues to plague the defense acquisition system.	
Cowap, S. A. (1998) Economic Incentives in Aerospace Weapon Systems Procurement, Master Thesis, LAI and Massachusetts Institute of Technology.	(Cowap, 1998) Download Link
Incentives are an instrument to reconcile conflicting goals between program office and contractor, or also between contractor and supplier. By linking the achievement of a goal that is important for one party with the achievement of a goal with another party, the severity of conflicting objectives may be reduced. It can also be used to make the achievement of a specific goal desirable to both parties. This work describes case studies that show that programs successfully use incentives by tailoring them to the specific goals and risks, and describes the tailoring process. It also contains examples of incentives, such as 1. Finance-related incentives: 1.1 Increased profit rate; 1.2 Sharing of cost saving benefits; 1.3 Reimbursement for investments; 1.4 Average unit procurement price; 1.5 Annual re-negotiation of firm fixed price contract; 2. Risk-related incentives: 2.1 Transfer of uncertain cost elements to program office; 2.2 Limited financial liability; 2.3 Limited future legal liability; 3. Process-related incentives: 3.1 Configuration control; 3.2 Variance in performance specifications; and 3.3 Granting of waivers.	
Kirtley, A. L. (2002) Fostering Innovation across Aerospace Supplier Networks, Master Thesis, LAI and Massachusetts Institute of Technology.	(Kirtley, 2002) Download Link
Suppliers play a central role in every program. They account for a large share of the total cost and technology content of major programs. Also, a significant share of technological innovation across many industries takes place at the interface between customer companies and their suppliers. Based on two case studies, this work develops recommendations on how to incentives suppliers for increased innovation.	

These incentives to supplier innovation are: 1. Differentiation of supplier relationships; 2. Excellent communication; 3. Sharing risk and investments; 4. Incentive mechanisms in contract structures; 5. Training and support; and 6. Appropriate levels of competition. Identified barriers to supplier innovation include: 1. Concern for secrecy and other communication barriers; 2. Uncertainty about the program's future; and 3. Government contracting practices failing to reward innovative efforts.	
Mandelbaum, J., Kaplan, W. S., McNutt, R. T. & Rebentisch, E. (2001) Incentive Strategies for Defense Acquisitions, Washington, D.C., Department of Defense.	(Mandelbaum et al., 2001) Request at LAI
Incentives should exist in every business arrangement because they maximize value for all parties. DoD needs to adopt strategies that attract, motivate, and reward contractors to encourage successful performance. Using commercial practices will enhance DoD's ability to attract nontraditional contractors. This guide amplifies existing policy regarding use of incentives in defense acquisitions. It explores cost-based and non-cost-based incentive strategies. It clearly defines use of performance objectives or product functionality vs. detailed requirements to seek best value acquisitions. It answers the following questions: 1. Why are we concerned with contractual incentives? 2. What elements contribute to an effective incentive strategy?, 3. How can we build and maintain an effective environment for a successful business relationship?, 4. How can we build the acquisition business case? And 5. How can we build an incentive strategy that maximizes value?	

8.4 LAI's Insights: Technology Integration

During Technology Integration, technologies for the design phase are selected and integrated into the program. The readiness of low-maturity technologies may be increased in parallel technology development tracks to a level that is suitable for their introduction into the design process. It includes the following activities:

8.4.1 Technology maturation monitoring

The main objective is to develop technologies to a level where the main risks regarding their cost and performance have been eliminated and they are fit to be integrated into an overall system. However, assessing the maturity level of a technology is not a trivial task, as certainty regarding its development status may be difficult to establish.

Publication Title & Synopsis	Citation & Download Link
Kenley, C. R. & Creque, T. R. (1999) Predicting Technology Operational Availability Using Technical Maturity Assessment. Systems Engineering, 2, 198-211.	(Kenley and Creque, 1999) Download Link
This paper reports research on the relationship of technology readiness and remaining time to technology introduction for nuclear stabilization technology. A technical maturity assessment method was performed by systems engineers in collaboration with a senior advisory panel composed of team members from different Department of Energy sites and from different engineering and science disciplines. Various stabilization technologies were assessed annually as to their relative maturity and availability for use in stabilizing nuclear materials. After 3 years of assessments, several of the technologies are now components of operational systems. A regression analysis of the historical assessments was performed, and it was concluded that the numerical technical maturity score produced by a team of experts provides a powerful predictor of the time remaining until the operational application of technologies.	
Tang, V. & Otto, K. N. (2009) Multifunctional Enterprise Readiness: Beyond the Policy of Build-Test-Fix Cyclic Rework. Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Design Theory and Design IDETC/DTM 2009 , August 30 - September 2, 2009, San Diego, California, 1-9.	(Tang and Otto, 2009) Request at LAI
NASA, the US Government and many companies attempt to manage the development and launch of new technology using Technology Readiness Levels, TRLs. Unfortunately, TRLs as generally defined are outdated and flawed, based on the extent of prototype or hardware use in the field. Urgency in improving TRL levels drives early release of hardware before it is ready, and initiates cyclic rounds of debugging and fixing failures in the field or laboratory. Such a build-test-fix approach to product development is now well documented to be inefficient and wasteful. We present updated definitions of technology readiness levels (TRLs) based on the lean and design-for-six-sigma product design methodology, a radical departure from the "build-test-fix" methodology of conventional TRLs. We argue that the iterative build-test-fix approach of cyclic rework is costly to product development, as well as, downstream manufacturing and services. We call our updated TRL the L-TRL, for Lean TRL. Consistent with our L-TRL, we also present updated definitions for Manufacturing Readiness Levels (MRLs) to address lean and six-sigma manufacturing principles. Hence we call them L-MRL. We address a void in the literature and unveil definitions for service readiness levels (SRLs).	

8.4.2 Technology transition management

This process addresses the integration of technologies that just reached sufficient maturity levels at R&D facilities into existing design and production processes at the main contractor and its suppliers.

Publication Title & Synopsis	Citation & Download Link
Shroyer, E. (2002) Lean Transition of Emerging Industrial Capability (LeanTEC), Final Report, Cooperative Agreement F33615-97-2-5153, U.S. Air Force and Boeing Company.	(Shroyer, 2002) Download Link
Technology transition from Research and Development to Product is not done as effectively as it should be in either government or industry. Industry invests an average of 3.5% of sales in R&D ($264B in FY2000). Of the projects that are expected to transition into production, only 20% to 60% do transition. Of those that transition, 60% are either late, have changes after transition, do not meet technical goals, or do not meet cost goals, while 5% of the projects experience all of these inefficiencies. Conservative monetary estimates for losses to industry are over $80B per year in waste and over $300B per year in lost savings. This research documents the result of surveys and best practice analysis in the aerospace and defense sector. A large number of recommendations regarding an efficient technology transition process are grouped into eight main process steps: 1. Establish technology transition process; 2. Create enabling environment for technology transition; 3. Select technology transition project portfolio; 4. Form team and execute technology transition projects; 5. Develop project charter and plans; 6. Establish communication protocols; 7. Promote efficient plan execution; and 8. Conduct formal reviews	
Pomponi, R. A. (1998) Organizational structures for technology transition: rethinking information flow in the integrated product team, Cambridge, MA, PhD thesis, LAI and MIT.	(Pomponi, 1998) Download Link
This research examines how organizational structure affects the implementation of new technology within an IPPD environment, focusing on information flow among integrated product teams (IPTs). Four unique information structures were identified in the first phase of the research, termed the management chain, focal point linkage, focal point inclusion, and network structures. The results of four in-depth case studies indicate that organizational structures which promote the flow of information to and from the IPT level contribute to a more effective technology transition process, as evidenced by the ability to deal effectively with organizational conflict, to coordinate across functional groups, and to plan for the future use of the technology in the firm. These structures were also shown to increase the ability of the manufacturing technology to positively influence the product design. Focal inclusion links between IPTs and a centralized technology transition function are recommended as a means to accomplish company-wide strategic goals within the focused development activity of the IPPD environment.	

8.5 LAI's Insights: Product Design

In Product Design, the system integration and its components are specified to a level that makes it fit for production. It consists of the following activities:

8.5.1 Product Design team organization

Product Design is a complex task that relies heavily on the integration of deep domain knowledge from various areas. This places high requirements not only on the leadership of PD teams, but also on the team members and the organization that provides them. In addition, integrated product teams for example bridge the gap between different organizations.

Publication Title & Synopsis	Citation & Download Link
Klein, J., Cutcher-Gershenfeld, J. & Barrett, B. (1997) Implementation Workshop: High Performance Work Organizations, Cambridge, MA, LAI Report RP97-02-34.	(Klein et al., 1997) Download Link
This report summarize key insights and learning by representatives from a cross section of organizations who are on the journey of implementing lean principles in order to achieve high performance work systems. The overall goal of the workshops and case studies was to facilitate learning about the implementation of high performance work organizations among LAI consortium members. Three case study presentations helped initiate the discussion. The two unionized cases were selected based on recommendations from the UAW and the IAM, while the Texas Instruments case was selected for the length of experience operating as a team-based work system. The key lessons learned address the areas of 1. Leadership, 2. Skill Development, 3. Measuring Progress, 4. Rewards and Incentives, and 5. Diffusion.	
Bernstein, J. I. (2000) Multidisciplinary Design Problem Solving on Product Development Teams, Cambridge, MA, PhD thesis, LAI and MIT.	(Bernstein, 2000) Download Link
This research studied how engineers from different specialties interpret and communicate about technical design problems while working on product development teams. Data was collected on 98 cases via interviews with engineers. The most important finding of this study was that engineers from different specialties do interpret the same problem differently. Specifically, two engineers were likely to evaluate the benefits or drawbacks of a potential solution using different sets of criteria. Thus, some design disputes were the result not of mutually exclusive needs but of a failure to recognize the different ways in which engineers were evaluating solutions to the problem. Furthermore, data collected during this study illustrated that in some cases these differences were the result of engineers addressing related, but unique problems. Therefore, a solution to one engineer's problem often created a new problem for another engineer on the team. A second conclusion of this study was that how design tools were used had a greater impact on a team's problem solving abilities than what tool was used. In this context, design tools included objects such as real or "virtual" prototypes as well as processes like simulations and tests. The results of this investigation suggested that such tools offered their greatest benefits when they were used in a participatory fashion in which a large fraction of a team shared in their use. Additionally, the more elements of a problem's context that were captured in a design tool, the greater its utility. Under such conditions, team members were able to create a shared evaluation system to judge potential solutions to the problem they were confronting, thereby facilitating problem resolution.	

Bresman, P. H. M. (2004) Learning Strategies and Performance in Organizational Teams, Cambridge, MA, PhD thesis, MIT and LAI.	(Bresman, 2004) Download Link
This research addresses the subject of team learning strategies and their performance effects in three areas. The first part explores team learning in an inductive study of six teams in one large pharmaceutical firm. Many of these teams engage in vicarious team learning — the activities by which a team learns key aspects of its task from the similar experiences of others outside the team — rather than experiential team learning. The nature of vicarious team learning is detailed in a model including three component processes: identification, translation, and application. The second part reviews the literature on team learning and concludes that it has largely been treated as a uniform construct. It is proposed that teams learn by deploying at least three different strategies: experiential learning, contextual learning, and vicarious learning. The third part examines different team learning strategies, and vicarious learning in particular, as a means to understanding learning and performance differences across teams. Vicarious learning is conceptualized as an integral part of how teams learn. A field study of 43 teams in the pharmaceutical industry is used to develop and test the construct and shows that vicarious learning is positively associated with performance.	
Susman, G. & Petrick, I. (1995) Product Development Team Effectiveness, Cambridge, MA, LAI Whitepaper 95-06.	(Susman and Petrick, 1995) Download Link
This study explores the relative influence of function managers and team leaders in managing integrated product development teams. It was prompted by the results of an earlier study which suggested that the most successful high risk projects had a 50/50 balance of influence in decision-making between function managers and team leaders. This study also suggested that in the most successful low risk projects, the balance of influence shifted heavily toward team leaders. The data from the current study suggest that too much influence toward team goals in daily decision-making may be counter-productive; however, the optimal point appears higher than 50/50 in the direction of team influence. Strong team leadership was shown to be important to project success in the earlier study. One of the ways in which strong team leadership may manifest itself is through influence over evaluating performance and determining rewards. Team leaders of successful projects also appear to form good working relationships with function managers who have different backgrounds and responsibilities than they do. Team leaders of successful projects focus more on resolving technical and production issues with function managers than on resolving priority and resource issues. They resolve such issues through compromise and problem-solving rather than relying on common superiors to resolve them or not resolving them at all. Finally, the optimal balance between goals, and influence over evaluation and rewards may vary over project phase.	
Browning, T. R. (1996) Systematic IPT Integration in Lean Development Programs, Cambridge, MA, Master's thesis, LAI and MIT.	(Browning, 1996) Download Link
This research investigates the use of different integrative mechanisms for Integrated Product Teams in lean product development. Program integration of cross-functional, upstream/downstream nature is required at three distinct levels: (1) within IPTs, (2) between IPTs but within higher level team groupings, and (3) between IPTs and higher level team groupings in a program at large. This work focuses on the second and third levels, realms of IPT interdependence, and categorizes several integrative mechanisms (IMs) that facilitate interteam integration. IMs are strategies and tools for effectively coordinating actions across team interfaces. The research is based on five case studies of different programs. The nine integrative mechanisms that are discussed are: 1.	

Systems engineering and interface optimization; 2. Improved information and communication technologies; 3. Training; 4. Col-location; 5. Town meetings / team building; 6. Manager mediation; 7. Participant mediation; 8. Interface management groups; and 9. Interface contracts and scorecards.	
Oehmen, J. (2005) Approaches to Crisis Prevention in Lean Product Development by High Performance Teams and through Risk Management. Munich and Cambridge, Technical University of Munich and LAI.	(Oehmen, 2005) Download Link
This thesis investigates factors that define high performance teams. Based on an extensive literature review, 49 factors are identified that have been used to describe high performance team. A system theory-based method is then used to cluster these factors into four groups, enablers, drivers, critical elements and indicators of high performance in teams. The clustering is verified by interviews in a product development organization. The factors in the different categories are discussed.	
Utter, D. A. (2007) Performing Collaborative, Distributed Systems Engineering (CDSE): Lessons Learned from CDSE Enterprises, Cambridge, MA, Master's thesis, LAI and MIT.	(Utter, 2007) Download Link
Previous research has demonstrated that the design practices of distributed design teams differ from those of traditional, co-located teams. However, many companies today are performing collaborative, distributed systems engineering (CDSE) using systems engineering (SE) processes and methods developed for traditional SE environments and are therefore encountering many issues. Successful SE practices are difficult to carry-out when performed by a traditional, colocated enterprise. The addition of geographic distribution and cross-company or intra-company collaboration in SE presents a myriad of social and technological challenges that necessitate new and different SE methods for success. In an attempt to benchmark the current state of CDSE practices in industry, this research presents the collection of CDSE lessons learned and success factors gathered from two case studies carried out at two aerospace and defense companies. The case studies examine many different factors that pertain to the companies' current CDSE efforts, including collaboration scenarios; collaboration tools; knowledge and decision management; SE practices and processes; SE process improvements; SE culture; SE project management, SE organization; and SE collaboration benefits and motivation.	

8.5.2 Integrated product and process development

As requirements and systems vary, the PD process has to be adapted accordingly. This is closely linked to the optimization of the value stream, for example with value stream mapping and the elimination of waste, as well as the selection of an appropriate development strategy, such as a waterfall model or set-based design.

Publication Title & Synopsis	Citation & Download Link
Pomponi, R. A. (1998) Organizational structures for technology transition: rethinking information flow in the integrated product team, Cambridge, MA, PhD thesis, LAI and MIT.	(Pomponi, 1998) Download Link
This research examines how organizational structure affects the implementation of new technology within an IPPD environment, focusing on information flow among integrated product teams (IPTs). Four unique information structures were identified in the first phase of the research, termed the management chain, focal point linkage, focal point inclusion, and network structures. The results of four in-depth case studies indicate that organizational structures which promote the flow of information to and from the IPT level contribute to a more effective technology transition process, as evidenced by the ability to deal effectively with organizational conflict, to coordinate	

across functional groups, and to plan for the future use of the technology in the firm. These structures were also shown to increase the ability of the manufacturing technology to positively influence the product design. Focal inclusion links between IPTs and a centralized technology transition function are recommended as a means to accomplish company-wide strategic goals within the focused development activity of the IPPD environment.	
Hernandez, C. M. (1995) Challenges and Benefits to the Implementation of Integrated Product Teams on Large Military Procurements, Cambridge, MA, Master's thesis, LAI and MIT.	(Hernandez, 1995) Download Link
This thesis analysis the challenges surrounding the implementation of integrated product teams (IPT) in military programs. It looks at this issue for four, ongoing, major aircraft developments; B2 Bomber, C17 Transport, F/A-18 E/F Fighter, and F22 Fighter. These four programs are reviewed and contrasted to commercial business practices to bring out structural differences that may act as barriers to IPT Implementation. Several areas were identified that impede its implementation. These areas include: training, team budget control, and the need for balance between teams and functions. In addition, details of how benefits can be derived from the IPT concept are discussed. These are reduced development time, team consensus decision making and improved communication. Current methods being used to measure these benefit are presented.	
Lucas, M. V. (1996) Supplier Management Practices of the Joint Direct Attach Munition Program, Cambirdge, MA, Master's thesis, LAI and MIT.	(Lucas, 1996) Download Link
The Joint Direct Attack Munition (JDAM) program reveals changes in the model for supplier relationships in the defense aerospace industry that have been accompanied by unprecedented results. Changes in decision-making, program structure, and organizational culture occurred as the result of reform measures and the product development administration of the program. The changes implemented by the Government as well as the innovative supplier management practices of the prime contractor showed progress in the general model for supplier relationships towards a more collaborative, team-oriented partnership. The linkages of the suppliers and the supplier designs resulted in innovations that changed the system architecture.	
Bozdogan, K., Deyst, J., Hoult, D. & Lucas, M. (1998) Architectural innovation in product development through early supplier integration. R&D Management, 28, 163-173.	(Bozdogan et al., 1998) Download Link
This paper explains how an important opportunity exists to pro-actively integrate suppliers at an early stage in the concept exploration and definition stages of product development. Research suggests that the concept of architectural innovation can be extended so that product features are matched with the associated specialized technical skills of partners in the development team. In addition to the establishment of integrated product teams, key enablers include: long-term commitment to suppliers; co-location; joint responsibility for design and configuration control; seamless information flow; and retaining flexibility in the definition of the system configuration.	

8.5.3 Product Design and System Engineering best practices

Some organizational concepts as well as processes have been identified as especially important for success. These are summarized in best practices that can be used for an internal benchmarking and to identify opportunities for improvement.

Publication Title & Synopsis	Citation & Download Link
Knoblinger, C.: PDSAT – A New Product Development Self-Assessment Tool. Technical University of Munich and Lean Advancement Initiative (http://lean.mit.edu), Munich and Cambridge, MA (2011)	(Knoblinger, 2011) Download Link
One approach companies can use to improve their product development performance is self-assessment to optimize their organization and processes. This thesis summarizes the current literature on PD-related self-assessment tools and derives tool requirements from an industry focus group (US aerospace and defense industry) as well as from interviews at a major American defense contractor. A gap analysis comparing these requirements to the previously identified tools is performed. The thesis concludes with the presentation of a new holistic self-assessment framework to be used in PD organizations. The framework includes a self-assessment questionnaire with 91 metrics, a formalized 9-step implementation process, tool customization guidelines, and mappings between the structure of the questionnaire and relevant process improvement approaches such as CMMI, Malcom Baldrige National Quality Award, Lean Management, and Six Sigma.	
Gordon, M., Musso, C., Rebentisch, E. & Gupta, N. (2009) The Path to Developing Successful New Products. The Wall Street Journal, November 30, 2009.	(Gordon et al., 2009) Download Link
This article summarizes the results of a product development best practice survey carried out by LAI and McKinsey. It was found—after surveying more than 300 employees at 28 companies across North America and Europe—that the businesses with the best product-development track records do three things better than their less-successful peers: They create a clear sense of project goals early on, they nurture a strong project culture in their workplace, and they maintain close contact with customers throughout a project's duration.	
Boehm, B., Valerdi, R. & Honour, E. (2008) The ROI of Systems Engineering: Some Quantitative Results for Software-Intensive Systems. Systems Engineering, 11, 221-234.	(Boehm et al., 2008) Request at LAI
This paper presents quantitative results on the return on investment of systems engineering from an analysis of the 161 software projects. The analysis shows that, after normalizing for the effects of other cost drivers, the cost difference between projects doing a minimal job of software systems engineering—as measured by the thoroughness of its architecture definition and risk resolution—and projects doing a very thorough job was 18% for small projects and 92% for very large software projects as measured in lines of code. The paper also presents applications of these results to project experience in determining “how much up front systems engineering is enough” for baseline versions of smaller and larger software projects, for both ROI-driven internal projects and schedule-driven outsourced systems of systems projects.	
Oppenheim, B.W., Murman, E.M., Secor, D.A.: Lean Enablers for Systems Engineering. Systems Engineering 14(1), 29-55 (2011).	(Oppenheim et al., 2011) Download Link
The emerging field of Lean Systems Engineering (LSE) is the application of Lean principles, practices, and tools to SE and to the related aspects of enterprise management (EM) in order to enhance the delivery of value (which is defined as flawless delivery of product or mission with satisfaction of all stakeholders) while	

reducing waste. The Lean Enablers for Systems Engineering is a comprehensive checklist of nonmandatory practices and recommendations formulated as "do's" and "don't's" of SE, and containing tacit knowledge (collective wisdom) on how to prepare for, plan, execute, and practice SE and EM using Lean Thinking. Each enabler has the potential to enhance program value and reduce waste. The Enablers are formulated as a web-based addendum to the current SE Handbook published by the International Council for Systems Engineering (INCOSE), and do not repeat the practices made therein, which are regarded as sound.	

8.5.4 Monitoring Product Design progress

Monitoring progress during PD can be particularly challenging, as many iterations and re-work of "finished" components may occur. Therefore, to allow for a better management of the process, the use of appropriate KPIs and leading indicators is very important.

Publication Title & Synopsis	Citation & Download Link
Roedler, G., Rhodes, D. H., Schimmoller, H. & Jones, C. (2010) Systems Engineering Leading Indicators Guide (Version 2.0), INCOSE-TP-2005-001-03.	(Roedler et al., 2010) Download Link
This guide describes the INCOSE systems engineering leading indicators. A leading indicator is a measure for evaluating the effectiveness of a how a specific activity is applied on a project in a manner that provides information about impacts that are likely to affect the system performance objectives. The leading indicators are: 1. Requirements Trend, 2. System Definition Change Backlog Trend, 3. Interface Trends, 4. Requirements validation trends, 5. Requirements verification tests, 6. Work product approval trends, 7. Review action closure trends, 8. Risk exposure trends, 9. Risk treatment trends, 10. Technology maturity trends, 11. Technical measurement trends, 12. Systems engineering staffing & skills trends, 13. Process compliance trends, 14. Facility and equipment availability trends, 15. Defect or error trends, 16. System affordability trends, 17. Architecture trends, and 18. Schedule and cost pressure.	
Rhodes, D. H., Valerdi, R. & Roedler, G. J. (2009) Systems Engineering Leading Indicators for Assessing Program and Technical Effectiveness. Systems Engineering, 12, 21-35.	(Rhodes et al., 2009) Request at LAI
This paper discusses a 3-year initiative to transform classical systems engineering (SE) measures into leading indicators, including the resulting guidance information that has been developed and future research directions. Contrary to simple status oriented measures typically used on most projects, leading indicators are intended to provide insight into the probable future state, allowing projects to improve the management and performance of complex programs before problems arise. This paper discusses the motivations and collaborative development of the SE leading indicators. It defines the leading indicator construct, introduces the initial set of 13 indicators, and provides guidance for implementation, analysis, and interpretation of these indicators. This work serves as a foundation for industry implementation and for further research to improve and expand the set of indicators, including development of a better understanding of how to best implement and use the leading indicators in a given program context.	

8.5.5 Product architecting

The architecture of a product has important implications on the fulfillment of customer requirements (e.g. modularity to allow for partial and continuous upgrades during the life cycle, decoupling of technology development cycles etc.). It also has a significant influence on how the PD process can be organized most effectively.

Publication Title & Synopsis	Citation & Download Link
Bador, D. (2007) Improving the Commonality Implementation in the Cockpit of Commercial Aircraft, Cambridge, MA, Master's thesis, LAI and MIT.	(Bador, 2007) Download Link
Judiciously implementing commonality across a range of products yields important benefits in product development. Thus, measuring the quality of commonality implementation is extremely beneficial for aircraft manufacturers. This thesis analyses the concept of commonality and divides it into three constructs that can help understand all of its aspects: 1. standardization, 2. reusability and 3. modularity. This work then presents a set of metrics measuring each of these aspects, from the point of view of the manufacturer and of the customer. The appropriateness of this set of metrics is tested in a case study analyzing the efficiency of commonality implementation in the cockpit of two well-known commercial aircraft families: the Airbus A320 family and the Boeing 737 family. This thesis further describes what additional analysis should be performed to validate the set of metrics for broader applications. After documenting the efficiency of the set of metrics, this thesis analyses the current practices of commonality management in commercial aviation.	
Boas, R. C. (2008) Commonality in Complex Product Families: Implications of Divergence and Lifecycle Offsets, Cambridge, MA, PhD thesis, LAI and MIT.	(Boas, 2008) Download Link
This dissertation leverages field research and a simple cost model to examine commonality in the context of complex product families. The core research effort was focused on conducting seven case studies of complex product families (aircraft, automobiles, satellites, and capital equipment). While the case studies provided a wealth of general insights, the studies were focused on examining divergence and lifecycle offsets, two critical topics that influence the benefits and penalties of commonality. Divergence refers to the tendency for commonality to reduce with time, for both beneficial and non-beneficial reasons. Lifecycle offsets refer to temporal differences between the lifecycle phases of product family members. Lifecycle offsets alter the potential benefits and penalties of commonality and their apportionment to individual products. Additionally, key factors identified during the literature review and case studies were translated into a simple two-product cost model of development and production in order to demonstrate key research insights in a more analytical manner.	
Nuffort, M. R. (2001) Managing Subsystem Commonality, Cambridge, MA, Master's thesis, LAI and MIT.	(Nuffort, 2001) Download Link
Common systems satisfy the requirements of multiple platforms and meet designated architecture, performance, life cycle cost, and interface standards. The analysis draws on eight case studies of both commercial and military aerospace organizations. While quantitative data on the benefits and costs of commonality in the defense aerospace industry is difficult to obtain, the case studies suggest that commonality can significantly reduce subsystem ownership costs by reducing both the cost of acquisition and the cost of operations and support. Subsystem commonality also increases mission effectiveness by reducing cycle time, improving reliability and availability, and guarding against diminishing manufacturing sources. The work	

indicates that commonality in the aerospace industry generally makes the most sense at the subsystem level, where different requirements are easier to reconcile and the strategy can have a significant impact on the logistics and supply systems. A common organization that manages across platforms, such as a product center of excellence, appears to offer the greatest potential advantage from commonality. The research reinforces the notion that strategies focusing only on the benefits of commonality in the acquisition phase of the life cycle are missing a significant portion of the holistic advantages of commonality from a system-level perspective. Platforms that deploy together and share common subsystems will likely have dramatically lower operations and support costs than platforms that might be common on the manufacturing floor but not in the field.	
Silva, L. M. (2001) A Partitioning Methodology for Helicopter Avionics System with a focus on Life Cycle Cost, Cambridge, MA, Master's thesis, LAI and MIT.	(Silva, 2001) Download Link
As one of the key responsibilities of a system architect, the decisions made with respect to how an avionics system is partitioned play a significant role in the system's Life Cycle Cost (LCC). Despite this, most of the decomposition methods available focus on managing the complexity of the system with respect to the architect's ability to understand the system. A framework was developed in order to quantify and compare the reliability and maintainability of five different helicopter avionics system architectures. The information was extracted from actual data collected during the maintenance of the five helicopter systems used by the US Government over a period of two years. Based on these five case studies, a set of partitioning criteria was developed that can be used in future programs in order to improve the LCC of the system. The methodology provides a process whereby the analysis of maintenance data can assist the system architect in making better architecting decisions. The process also identified some additional factors that have an impact on the LCC. The most compelling was that of legacy subsystems that offer significant problems with respect to their partitioning due to the fact that they are more entrenched in the current avionics market.	
Mahé, V. R. (2008) A Survey of Front End Modularity as an Automotive Architecture and its Ability to Deliver Value, Cambridge, MA, Master's thesis, MIT.	(Mahé, 2008) Download Link
The partitioning of a system dictates the creative space for a designer or engineer. This thesis analyzes how using a new automotive architecture known as a Front End Module (FEM) can affect a limited specific subset of stakeholders. Through the use of interviews of subject matter experts, literature research and the use of System Design Management tools, an in depth analysis was done on the FEM and how it affects the craftsmanship, damageability and assembly attributes. It was shown how the craftsmanship attribute can be improved through the strategic use of FEM's to allow for a feed-forward system where build data are incorporated into upcoming FEM builds. Even with this advantage, the FEM architecture will not negatively impact the damageability attribute or assembly attribute if the proper design cues and strategies are followed. The FEM was also evaluated as an architecture itself through the specific and targeted intent and beneficiary breakdown. The analysis included an Object/Process Mapping analysis where it was proposed that the true customer of the automotive front end is not the individual that purchased the vehicle but rather the visual society as a whole. Finally, a managerial approach was taken for the analysis of the inherent supplier relationship that is required with using this FEM architecture. Interviews were conducted with two suppliers of OEM's and their common road blocks were analyzed such as lack of holistic thinking or failure to understand the role of the system integrator.	

Beckert, M. T. (2000) Organizational Characteristics for Successful Product Line Engineering, Cambridge, MA, Master's thesis, LAI and MIT.	(Beckert, 2000) Download Link
The evaluation of strategic, political, and cultural characteristics at four organizations implementing product line engineering (PLE) was conducted. The objective of this research was to identify non-technical characteristics that attribute to successful product line engineering efforts. A set of questions structured around defined strategic, political, and cultural characteristics was generated for formal evaluation of each organization, and then a series of interviews within each organization was performed to gather case study data. Two of the four organizations studied were identified as being more successful with product line engineering, and, thus, were used as the basis for comparison. A comparative analysis of the organizations was performed to observe noteworthy characteristics that attributed to success. These include: 1. Strategic plans clearly defined goals relating to the development of product lines; 2. Metrics were used that applied specifically to product line engineering; 3. PLE strategies were implemented uniformly across the organization; 4. The smallest percent of projects for each organization utilized the new design strategy; 5. Organizing resources around platforms, using modular system architectures, and implementing initiatives to standardize components facilitated resource and technology sharing; and 6. By defining and enforcing product line strategies, senior management enabled successful product line engineering	
Cunningham, T. W. (1998) Chains of Function Delivery: A Role for Product Architecture in Concept Design, Cambridge, MA, PhD thesis, LAI and MIT.	(Cunningham, 1998) Download Link
This research intends to improve three areas of team performance in concept design and architecting: the team's understanding and recognition of the product architecture, the team's ability to document integration issues and risks, and the team's ability to judge whether a product concept is worthy of further pursuit. In this context, two themes are explored. First, a systematic procedure for identifying integration issues in mechanical assemblies is developed. The procedure captures chains: graphical representations of how product-level attributes are delivered, depicted on a hierarchy of the physical elements. Chains, which differ for each concept and decomposition, show 1) which functions are delivered in integral fashion, and 2) which elements play a role in delivering each function. Represented graphically, chains can help the multi-disciplinary team relate the diverse technical and non-technical influences on decomposition and architecture. Metrics can then be applied to reveal the integration issues and integration risk associated with many, potentially conflicting chains. The research applies established part locating mathematics in the procedure, expanding the utility of this existing idea by applying it to concept design. Second, the thesis develops a method for conducting a chain analysis of candidate concepts and decompositions, creating a framework for trade-offs in the context of architecture. The method and chain procedure and metrics are tested on the Lockheed Martin Joint Strike Fighter military aircraft.	

8.5.6 Value Stream Optimization

The creation of stakeholder value is the ultimate goal in product design. Several tools from Lean Product Development are available to model and improve the flow of value while eliminating waste. The challenge lies in the identification of value and discerning wasteful activities from necessary, but non-value creating activities.

Publication Title & Synopsis	Citation & Download Link
Oehmen, J. & Rebentisch, E. (2010) Waste in Lean Product Development. LAI Paper Series "Lean Product Development for Practitioners". Cambridge, MA, LAI and MIT.	(Oehmen and Rebentisch, 2010c) Download Link
This whitepaper summarizes the LAI research to-date on waste in lean product development. It contains an introduction to the concept of value and waste in Lean PD. This is followed by a detailed discussion of the eight types of waste in Lean PD: 1. Over production of information; 2. Over processing of information; 3. Miscommunication of information; 4. Stockpiling of information; 5. Generating defective information; 6. Correcting information; 7. Waiting of people; and 8. Unnecessary movement of people. Next, the whitepaper explains the process of Value Stream Mapping and gives a detailed example. The whitepaper concludes with a summary of the remaining relevant LAI literature in the areas of 1. Types of waste and waste identification; 2. PD value and value stream mapping; and 3. Application of PD value stream mapping.	
The following documents are a selection of the many documents covered by the LAI Waste in Lean PD Whitepaper (see above)	
Pessôa, M. V. P. (2008) Weaving the waste net: a model to the product development system low performance drivers and its causes, Cambridge, MA, LAI White Paper 08-01.	(Pessôa, 2008) Download Link
This report is based on an extensive review of LAI and non-LAI literature to develop an overview of different types of waste. The descriptions in Section 4 are based on this body of work. His structure also included two more types of waste, 'wishful thinking' and 'external events'. In the overview presented here, these are not treated as types of PD waste as such, but as possible underlying root causes. His work also includes a method to prioritize different types of waste according to the extent by which they influence and are influenced themselves by other types of waste, as well as an approach to identify system-level root causes of wastes in order to prioritize improvement efforts.	
Kato, J. (2005) Development of a Process for Continuous Creation of Lean Value in Product Development Organizations, Master Thesis. LAI and Massachusetts Institute of Technology.	(Kato, 2005) Download Link
This thesis presents a very detailed empirical analysis of three projects, conducting a value stream analysis, waste identification and waste quantification. His work therefore belongs to three categories: Defining and identifying different types of waste, extending the method of value stream analysis, and conducting and documenting a very detailed value stream analysis (also see the example in Section 0). In addition to the elements of his work already part of this overview, of special interest are the additional notations that he develops to discern different types of waste graphically in a value stream map, as well as the detailed root cause analyses that he performs for several types of waste.	
McManus, H. (2005) Product Development Value Stream Mapping (PDVSM) Manual, Cambridge, MA, Lean Advancement Initiative (LAI) at MIT.	(McManus, 2005) Download Link

This document provides a detailed to guide to perform a value stream mapping and analysis in a product development system. A value stream mapping aims at optimizing the flow of value through a PD system by identifying and removing waste. It consist of four main phases: 1. Preparatory phase; 2. Mapping of the current value stream; 3. Identification of waste; and 4. Process improvement.	

8.5.7 Product Design strategy

A number of strategies or process families can be chosen for designs that have strong implications for all other program processes and the way that users and customers are integrated. These include evolutionary acquisition, waterfall model and set-based design.

Publication Title & Synopsis	Citation & Download Link
Ferdowsi, B. (2003) Product Development Strategies in Evolutionary Acquisition, Cambridge, MA, Master's thesis, LAI and MIT.	(Ferdowsi, 2003) Download Link
The Air Force has decided to implement an Evolutionary Acquisition strategy, meaning the development process focuses on delivering incremental capabilities through short increments or spirals. The hypothesis of this research is that the decision for or against Evolutionary Acquisition for a program should be based on attributes of the product, the program goals, the uncertainties, and stakeholder involvement. A number of case studies were performed specifically targeting programs identified as evolutionary. From the case studies a number of key recommendations were made for program managers and policy makers implementing Evolutionary Acquisition, as well as a notional illustration of product development selection. Specifically, the research found that programs with high user requirements uncertainty tended towards more iteration, while programs with significant technical and performance goals had less iteration and greater planning. In programs where rapid delivery was the goal and uncertainties were relatively low, incremental strategies were found to be most applicable. Recommendations included implementing open architecture systems through owning system interfaces, managing stakeholder expectations through system representations and internal change agents, and providing stable funding and contingency funds for rapid change implementation. Additional recommendations were made on implementing testing and logistics in highly iterative programs.	
Tondreault, J. P. (2003) Improving the Management of System Development to Produce More Affordable Military Avionics Systems, Cambridge, MA, Master's thesis, LAI and MIT.	(Tondreault, 2003) Download Link
This thesis aims to improve the management of system development to deliver more affordable systems. This research is different than most literature published on affordability because it focuses on design innovation as opposed to product development and manufacturing efficiency through Lean, Six-Sigma or other techniques. Four areas are investigated: the nature of development focus during each design iteration, the role of requirements, managing lifecycle cost as a design requirement and effective integration of downstream knowledge into the design. A model for developing requirements that strikes a better balance between performance and lifecycle cost is suggested – treating lifecycle cost as a design requirement and explicitly focusing on understanding the cost-performance trade space before developing requirements. A product development model is suggested – focusing on achieving lifecycle cost goals first and using iterations to grow performance can lead to lower cost solutions. Both the requirements development and product development models require leveraging prior knowledge, technology and capability. The requirements model requires high knowledge of system cost drivers and achievable	

performance. The product development model requires low technical risk allowing the team to focus on affordability first without running unacceptable levels of performance risk. Methods for increasing the effective integration of downstream knowledge are also discussed.	
Roberts, C. J. (2003) Architecting Evolutionary Strategies Using Spiral Development for Space Based Radar, Cambridge, MA, Master's thesis, LAI and MIT.	(Roberts, 2003) Download Link
This thesis investigates the use of Spiral Development strategies for a space system. Spiral Development was originally developed in the software industry, and a consensus has not yet emerged about its applicability to space systems, for example the Space Based Radar (SBR). In addition, space systems typically have not been developed with explicit considerations of architectural modularity and scalability, features necessary to enable evolutionary acquisition strategies. A stakeholder based system architecting process known as Multi-Attribute Tradespace Exploration (MATE) provides a framework for combining computer based modeling and simulation of complex engineering systems with decision theory. Qualitative comparisons between software systems and SBR in the context of spiral development suggest a fundamental difference in system evolution and risk mitigation strategies, yet found the Spiral Development and Evolutionary Acquisition framework to be suitable to SBR. Policy recommendations for improving cost accounting, key stakeholder participation, and evolutionary options analysis were made based on findings of the research.	
Stagney, D. B. (2003) The Integrated Concurrent Enterprise, Cambridge, MA, Master's thesis, LAI and MIT.	(Stagney, 2003) Download Link
Within the context of large-scale projects, this thesis analyzes several of the current and emerging business processes that have been introduced in order to improve upon the decomposition method. Techniques such as QFD, DSM, IPPD, MDO, ICE and MATE-CON are analyzed by way of a three-dimensional Concurrent Engineering framework. An in-depth case study based on 15-months of work shows how the implementation of Integrated Concurrent Engineering (ICE) can dramatically improve the quality and speed of the design process, and can promote innovation and learning. Team metrics are presented and analyzed. As measured theoretically and practically, no single approach discussed in the paper brings a satisfactory resolution to the challenges identified. Despite their initial successes, even the case study team failed to strike a balance between the technology, people and process elements that must be systematically managed in order to create and sustain excellence in any complex undertaking. The structure of the team's corporation – the financial, organizational and human resource processes – have stalled the case study team just short of an enterprise-wide breakthrough. Finally, radical improvements in business productivity will not be achieved through the incremental improvements discussed above. Rather, the very nature of the corporation must be re-thought and re-born. The thesis presents a vision for the Integrated Concurrent Enterprise along with a concept of operations and detailed implementation guide.	
Bernstein, J. I. (1998) Design Methods in the Aerospace Industry: Looking for Evidence of Set-Based Practices, Cambridge, MA, Master's thesis, LAI and MIT.	(Bernstein, 1998) Download Link
Set-based concurrent engineering (SBCE) seems to offer advantages over more traditional techniques. This research had three goals: 1) to develop a clear understanding of the definition of SBCE and to contrast that definition with other theories, 2) to assess the "set-basedness" of the aerospace industry, and 3) based on the assessment, to propose a model for implementing SBCE within an aerospace	

development project. While set-based concurrent engineering consists of a wide variety of design techniques, the basic notions can be stated in two principles: 1) engineers should consider a large number of design alternatives, i.e., sets of designs, which are gradually narrowed to a final design, and 2) in a multidisciplinary environment, engineering specialists should independently review a design from their own perspectives, generate sets of possible solutions, and then look for regions of overlap between those sets to develop an integrated final solution. This research found that while no company's design process completely fulfilled both of these criteria, many set-based techniques are used within the aerospace industry. Building on some of the observed industry practices, a design process model is proposed which combines concepts from lean manufacturing, such as "flow" and "pull," to implement set-based concurrent engineering.	

8.5.8 Testing & prototyping

This activity is relevant both to technology development as well as product design. In technology development, the testing and prototyping would focus on single components or technologies, whereas in product design, the entire system (or major components) would be tested. This is the main activity to verify that a certain performance level has been reached, and component and system requirements are met. Developing testing and prototyping protocols that assure a necessary level of certainty while minimizing cost is a very challenging task.

Publication Title & Synopsis	Citation & Download Link
Weigel, A. L. (2000) Spacecraft System-Level Integration and Test Discrepancies: Characterizing Distribution and Costs, Cambridge, MA, Master's thesis, MIT and LAI.	(Weigel, 2000) Download Link
The goal of this research is to characterize the distribution and costs of spacecraft discrepancies found at the system level of integration and test, as well as understand the implications of those distributions and costs for the spacecraft enterprise as a whole. Spacecraft discrepancies are analyzed in this work on the basis of the following categories: 1. the spacecraft mission, 2. the spacecraft subsystem where the discrepancy occurred, 3. the date of the discrepancy occurrence, 4. the discrepancy report open duration, 5. the immediate action taken to fix the discrepancy (disposition), 6. the root cause of the discrepancy, 7. the long-term corrective action prescribed to prevent the discrepancy from happening again on future spacecraft, 8. the labor time spent on the discrepancy, and 9. the cycle time lost due to the discrepancy. A statistical analysis forms the basis for research findings at the enterprise level in the areas of quality yield, resource utilization, stakeholder satisfaction and flow time. Recommendations to enterprise stakeholders for increasing the value derived from system-level integration and test follow from the enterprise-level findings.	
Carreras, C. E. (2002) Opportunities for Lean Thinking in Aircraft Flight Testing and Evaluation, Cambridge, MA, Master's thesis, LAI and MIT.	(Carreras, 2002) Download Link
This paper investigates whether Lean principles can be applied to aircraft flight testing and evaluation to help meet these goals. Specific objectives are to identify opportunities for the implementation of Lean thinking and establish a framework for structured implementation of Lean principles and practices. This study focuses on seven aircraft programs: 737-NG, 767-400, Hawker Horizon, F-22, F/A-18E/F, C-130J, and the T-6A. The programs are analyzed from a programmatic viewpoint to identify where lean practices are currently being used and how lean thinking could further	

improve the overall flight testing process. Opportunities were identified in: coordination of the systems engineering value stream, coordination with other test aircraft and necessary support functions, and management of the daily test operations.	
Deonandan, I., Valerdi, R., Lane, J. A. & Macias, F. (2010) Cost and Risk Considerations for Test and Evaluation of Unmanned and Autonomous Systems of Systems, Loughborough, UK, 5th IEEE International Conference on Systems of Systems Engineering, June 2010.	(Deonandan et al., 2010) Request at LAI
The evolutionary nature of Unmanned and Autonomous systems of systems (UASoS) acquisition needs to be matched by evolutionary test capabilities yet to be developed. As part of this effort we attempt to understand the cost and risk considerations for UASoS Test and Evaluation (T&E) and propose the development of a parametric cost model to conduct trade-off analyses. This paper focuses on understanding the need for effort estimation for UASoS, the limitations of existing cost estimation models, and how our effort can be merged with the cost estimation processes. We present the prioritization of both technical and organizational cost drivers. We note that all drivers associated with time constraints, integration, complexity, understanding of architecture and requirements are rated highly, while those regarding stakeholders and team cohesion are rated as medium. We intend for our cost model approach to provide management guidance to the T&E community in estimating the effort required for UASoS T&E.	
Hess, J., Agarwal, G., Deonandan, I., Kenley, B., Mikaelian, T. & Valerdi, R. (2010) Normative and Descriptive Models for Test & Evaluation of Unmanned and Autonomous Systems of Systems, Chicago, IL, 20th INCOSE Symposium, July 2010.	(Hess et al., 2010) Request at LAI
The United States Department of Defense has purchased and deployed many unmanned autonomous systems and will continue to do so at an ever-increasing rate in the years to come. Our research aims to address a number of questions posed by members of DOD's acquisition workforce that are related to testing and evaluation of these systems. This paper defines a small set of normative (ideal) and descriptive (actual) frameworks for test and evaluation. Our research will use these models as a step toward identifying the best prescriptive advice to give the DOD through PATFrame (Prescriptive and Adaptive Testing Framework), the decision support system we are developing. We describe tests strategies used in the DARPA Grand Challenge competition and the SPHERES test bed and suggest ways in which the DOD can learn from these experiences.	
Hess, J. T. & Valerdi, R. (2010) Test and Evaluation of a SoS using a Prescriptive and Adaptive Testing Framework, Loughborough, UK, , 5th IEEE International Conference on Systems of Systems Engineering, June 2010.	(Hess and Valerdi, 2010) Request at LAI
Testers need the ability to adapt test planning on the order of days and weeks. PATFrame will use its reasoning engine to prescribe the most effective strategies for the situation at hand. Strategies in this context include methods of experimental designs, test schedules and resource allocation. By facilitating rapid planning and re-planning, the PATFrame reasoning engine will enable users to use information learned during the test process to improve the effectiveness of their own testing rather than simply follow a preset schedule. This capability is particularly attractive in the domain of Systems of Systems testing because the complexity of test planning and scheduling make frequent re-planning by hand infeasible.	

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